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ARFIMA Reference Forecasts for Worldwide CO_2 Emissions and the Need for Large and Frontloaded Decarbonization Policies

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ARFIMA Reference Forecasts for Worldwide CO_2 Emissions and the Need for Large and Frontloaded Decarbonization Policies [1]

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Abstract

We provide reference forecasts for worldwide CO2 emissions from fuel fossil combustion and cement production based on an ARFIMA approach. Our projections suggest a time path for emissions that is inconsistent with the general IPCC decarbonization goals. Indeed, we project emissions to increase, over the next three decades, to levels about 11-12% above the 2010 level. For the IPCC goals to be achieved it is necessary to reduce emissions by 57.4% and 97.4% of 2010 emissions by 2030 and 2050, respectively. Furthermore, the bulk of these efforts have to take place by 2030. This implies that the policy efforts necessary to achieve such goals are not only daunting but also frontloaded. Finally, the presence in the data of long memory with mean reversion suggests that policies must be persistent to ensure that these reductions in emissions are also permanent. These results add to the sense of urgency in dealing with the issue of decarbonization. The policy efforts necessary to achieve IPCC decarbonization goals are urgent, daunting and frontloaded.

JEL Classification: C22, C53, O52, Q54

Keywords: Worldwide CO_2 emissions; IPCC emission targets; long memory; ARFIMA

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[1] This is one of two twin papers on the issue of developing new reference CO2 emissions forecasts and identifying their implications for the policy efforts towards decarbonization. The other paper "ARFIMA Reference Forecasts for Worldwide CO2 Emissions and the National Dimension of the Policy Efforts to Meet IPCC Targets" focuses on aggregate worldwide CO2 emissions by country – China, USA, EU, India, Russia, Japan, and Rest of the World.

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1. Introduction

The purpose of this article is to provide reference forecasts for worldwide CO_2 emissions based on an ARFIMA approach. We consider both aggregate emissions and each of its main sources – solid fuels, liquid fuels, gas, gas flaring, and cement production. Our ultimate objective is to compare our reference forecasts with the recent IPCC emissions targets and thereby ascertain the nature of the policy efforts necessary to achieve such targets.

There is strong scientific evidence confirming the warming the planet's climate system, with increasing temperature of the atmosphere and oceans, rising sea levels, melting ice, among others, whose most likely causes are the increased concentration of anthropogenic greenhouse gas emissions in the atmosphere [see IPCC (2014)].

Recently, the IPCC (2018) report has pointed that limiting global warming to 1.5°C would require "rapid and far-reaching" transitions in land, energy, industry, buildings, transport, and cities. Global net anthropogenic emissions of CO_2 would need to fall by about 45% from 2010 levels by 2030, reaching 'net zero' by 2050. As the IPCC suggests that the natural carbon sequestration capacity will be approximately 15% of the 2010 levels, carbon neutrality implies by 2050 a reduction of 85% relative to 2010 levels.

The question remains, however, as to the magnitude and timing of the policy efforts necessary to achieve such policy targets. In turn, identifying the proper reference scenario is critical first step in ascertaining the extent of the policy effort required, and thereby determining the costs involved in achieving such goals.

Specifying a reference scenario, as in the typical "business as usual" projections, means predicting a path to CO_2 emissions that reflect existing demographic trends, prospective trends for energy and industrial processes, for the services, residential, transport and waste sectors, as well as, ongoing policy commitments. This conventional approach to establishing reference scenarios, however, introduces a large number of working assumptions and a great degree of arbitrariness in their specifications, thereby clouding the information it intends to provide.

This paper uses an ARFIMA approach to provide reference forecasts for CO_2 emissions based on a comprehensive univariate statistical analysis of the different time series and recognizing the possible presence of long-memory through fractional integration. Accordingly, our forecasts are rooted on the most basic statistical fundamentals of the stochastic processes that underlie emissions. As such, they capture the information included in the sample, and implicitly assume that the observed trends will continue in the future. Thus, these forecasts provide the most fundamental reference case forecast of CO_2emissions. [See Belbute and Pereira (2015, 2017)].

There is now an extensive literature on fractional integration, which considers the possibility that variables may follow a long memory process [see, among others, Diebold and Rudebusch (1991), Lo (1991) Sowell (1992a) and Palma (2007)]. The ARFIMA methodology is inspired by a budding literature on the analysis of energy and CO_2emissions based on a fractional integration approach [see, for example, Barassi et al.(2011), Apergis and Tsoumas (2011, 2012), Barros et al. (2016) and Gil-Alana et al. (2015) and Belbute and Pereira (2015, and 2017)].

The fractional integration approach goes well beyond the stationary/non-stationary dichotomy to consider the possibility that variables may follow a long memory process. This long-range dependence is characterized by a hyperbolically-decaying autocovariance function, and by a spectral density that approaches infinity as the frequency tends to zero. Long memory means a significant dependence between observations widely separated in time, and, therefore, the effects of policy shocks may be temporary but long lasting.

Measuring the persistence of CO_2 emissions is of utmost importance for the specification of long-term reference case scenarios for emissions as well as for the design of energy and environmental policies. If emissions are stationary, then transitory public policies will tend to have only transitory effects. Permanent changes, therefore, require a permanent policy stance. On the other hand, if emissions are not stationary, then even transitory policies will have permanent effects on emissions, and a steady policy stance is less critical. Long memory is an intermediate case in which the policy stance needs to be steady but the effects of transitory policies are long lasting.

The remainder of this paper is organized as follows. Section 2 presents and describes the data set. Section 3 provides a brief technical description of the methodology used. Section 4 discusses the empirical findings, considering first the fractional integration analysis and then the accuracy of in-sample forecasts. Section 5 presents and discusses our reference forecasts vis-à-vis the IPCC new targets. Finally, section 6 provides a summary of the results, and discusses their policy implications.

2. Data: Sources and Description

2.1 Data Sources

In this paper, we use annual data for global CO_2 emissions for the period between 1950 and 2017. The data until 2014 is from the Carbon-Dioxide Information Analysis Centre [see Boden et. al. (2016)]. This data set contains information going back to 1870. Nevertheless, in this work we have elected to work only with data starting in 1950, given the profound structural changes that occurred after World War II. In turn, data for 2015-2017 is from the national emissions inventories collected by the United Nations [see UNFCCN (2018)] and reported by Global Carbon Atlas (2019).

Aggregate CO_2 emissions are the sum of five components: emissions from burning fossil fuels – solid, liquid, gas, and gas flaring, and emissions from cement production. The data do not consider emissions from land use, nor from land-use change and forestry. All variables are measured in million metric tonnes of carbon per year (Mt, hereafter), and were converted into units of carbon dioxide by multiplying the original data by 3.664, the ratio of the two atomic weights.

2.2 Description of the Data

Table 1 presents summary information about our data. The first column shows the value of the global CO_2 emissions in the first year of each decade while the remaining columns show the mean shares in total emissions for the decade of each of the emissions sources.

[Insert table 1 around here]

Over the sample period, worldwide CO_2 emissions grew consistently. Nevertheless, we can identify two distinct periods. Between 1950 and 1980, global emissions grew at an annual average rate of 4.1%, reaching 19,628.1 Mt in 1979. More recently, the average annual growth rate fell to 1.7%. By 2017, emissions reached their highest value ever at 36,767 Mt, a value that is 10% above the 2010 levels.

Combustion of solid fuels was the dominant source of CO_2 emissions during the first two decades of our sample period, contributing on average to around 53.5% of total emissions. In 2017, however, this figure was just 39.6% of total emissions. Over the sample period, the emissions from fossil fuel combustion averaged 38.9% of total emissions.

Combustion of liquid fuels accounted on average for 37.7% for total CO_2 emissions over the sample period. In the first three decades, this share increased from 29.7% in the 1950s to 47.2% in the 1970s. Since 1980, however, it declined reaching 34.4% in 2017.

CO_2 emissions from gas represent 17.9% of total emissions over the sample period. In the 1950s they were 7.3% of emissions and increased to 12.9% in the 1970s. In subsequent decades, the relative importance of these emissions continuously increased although at a slower pace. In 2017, they reached their highest value with 19.6% of total emissions.

CO_2 emissions from cement production account for 3.2% of total emissions over the sample period. The relative share of emissions from cement production showed a persistently increasing pattern reaching 5.7% in 2017. Finally, CO_2 emissions from gas flaring account for 1.0% of total emissions over the sample period. After 1980s, the relative share of CO_2 emissions from gas flaring declined to reach 0.7% % in 2017.

3. Fractional Integration

3.1 Fractionally-Integrated Processes

A fractionally-integrated process is a stochastic process with a degree of integration that is a fractional number, and whose autocorrelations decay slowly at a hyperbolic rate of decay. Accordingly, fractionally-integrated processes display long-run rather than short-term dependence and for that reason are also known as long-memory processes

A time series $x_t = y_t - \beta z_t$ is said to be fractionally integrated of order d, if it can be represented by

$$(1-L)^d x_t = u_t, \qquad t = 1, 2, 3, ... \qquad (1)$$

where, β is the coefficients vector, z_t represents all deterministic factors of the process, y_t, and $t = 1, 2, ... n$, L is the lag operator, d is a real number that captures the long-run effect, and u_t is $I(0)$.

Allowing for values of "d" in the interval between 0 and 1 gives an extra flexibility that may be important when modeling long-term dependence in the conditional mean. Indeed, in contrast to an $I(0)$ time series (where $d = 0$) in which shocks die out at an exponential rate, or an $I(1)$ process (where $d = 1$) in which there is no mean reversion, shocks to the conditional mean of an $I(d)$ time series with $0 < d < 1$ dissipate at a slow hyperbolic rate. More specifically, if $-0.5 < d < 0$, the autocorrelation function decays at a slower hyperbolic rate but the process can be called anti-persistent, or, alternatively, to have rebounding behavior or negative correlation. If $0 < d < 0.5$, the process reverts to its mean but the auto-covariance function decreases slowly as a result of the strong dependence on past values. Nevertheless, the effects will last longer than in the pure stationary case ($d = 0$). If $0.5 < d < 1$, the process is non-stationary with a time-dependent variance, but the series retains its mean-reverting property. Finally, if $d \geq 1$, the process is non-stationary and non-mean-reverting, i.e. the effects of random shocks are permanent [for details see, for example, Granger and Joyeux (1980), Granger (1980, 1981), Sowell (1992a, 1992b), Baillie (1996), Palma (2007) and Hassler et all (2016), Belbute and Pereira (2015)].

3.2 ARFIMA Processes

An ARFIMA model is a generalization of the ARIMA model which frees it from the I(0)/I(1) dichotomy, therefore allowing for the estimation of the degree of integration of the data generating process. In an ARMA process the AR coefficients alone are important to assess whether or not the series is stationary. In the case of the ARFIMA model, the $AR(p)$ and $MA(q)$ terms are treated as part of the model selection criteria. Accordingly, the ARFIMA approach provides a more comprehensive and yet more parsimonious parameterization of long-memory processes than the ARMA models. Moreover, in the ARFIMA class of models, the short-run and the long-run dynamics is disentangled by modeling the short-run behavior through the conventional ARMA polynomial, while the long run is captures by the fractional differencing parameter, d [see, among others, Bollerslev and Mikkelsen (1996)].

If the process $\{u_t\}$ in (1) is an $ARMA(p,q)$, then the process $\{x_t\}$ is an $ARFIMA(p,d,q)$ process and can be written as

$$\phi(L)(1-L)^d x_t = \theta(L)e_t \tag{2}$$

where

$$\phi(L) = 1 - \phi_1 L - \phi_2 L^2 - \ \dots \ - \phi_p L^p = 0$$
$$\theta(L) = 1 + \theta_1 L + \theta_2 L^2 + \ \dots \ + \theta_p L^q = 0$$

are the polynomials of order p and q respectivelly, with all zeroes of lying outside the unit circle, and with e_t as white noise. Clearly, the process is stationary and invertible for $-0.5 < d < 0.5$.

The estimation of the parameters of the ARFIMA model $\phi,\ \theta,\ d,\ \beta$ and σ^2 is done by the method of maximum likelihood. The log-Gaussian likelihood of y given parameter estimates $\hat{\eta} = (\hat{\phi}, \hat{\theta}, \hat{d}, \hat{\beta}, \hat{\sigma}^2)$ was established by Sowell (1992b) as

$$\ell\big((y|\hat{\eta})\big) = -\frac{1}{2}\{\boldsymbol{T}\log(2\pi) + \log|\widehat{\boldsymbol{V}}| + \boldsymbol{X}'\widehat{\boldsymbol{V}}^{-1}\boldsymbol{X}\} \tag{3}$$

where X represents a $\boldsymbol{T}$- dimensional vector of the observations on the process $x_t = y_t - \beta z_t$ and the covariance matrix $\boldsymbol{V}$ has a Toeplitz structure.

3.3 ARFIMA Forecasting and Prediction-Accuracy Assessment

Given the symmetry properties of the covariance matrix, $\boldsymbol{V}$can be factored as $\boldsymbol{V} = \boldsymbol{LDL}'$, where $\boldsymbol{D} = \mathrm{Diag}(v_t)$ and $\boldsymbol{L}$ is lower triangular, so that;

$$\boldsymbol{L}' = \begin{bmatrix} 1 & 0 & 0 & \dots & 0 \\ \tau_{1,1} & 1 & 0 & \dots & 0 \\ \tau_{2,2} & \tau_{2,1} & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tau_{(T-1),(T-1)} & \gamma_{(T-1),(T-2)} & \tau_{(T-1),(T-3)} & \dots & 1 \end{bmatrix} \tag{4}$$

Moreover, let $\tau_t = V_t^{-1}\gamma_t$, $\gamma_t = (\gamma_1,\ \gamma_2, \dots ,\ \gamma_t)'$ and V_t is the $t\ \times\ t$ upper left sub-matrix of $\boldsymbol{V}$.

Let $f_t = y_t - \beta z_t$. The best linear forecast of x_{t+1} based on $x, x_2, \dots\ x_t$ is

$$\hat{f}_{t+1} = \sum_{k=1}^{t} \tau_{t,k} f_{t-k+1} \tag{5}$$

Moreover, the best linear predictor of the innovations is $\hat{\varepsilon} = L^{-1}f$, and the one-step-ahead forecasts for $\hat{y}$, in matrix notation, is

$$\hat{y} = \hat{L}^{-1}(y - Z\hat{\beta}) + Z\hat{\beta}. \tag{6}$$

Forecasting is carried out as suggested by Beran (1994) so that $\hat{f}_{T+k} = \tilde{\gamma}_k' \hat{V}^{-1} \hat{f}$, where $\tilde{\gamma}_k = (\hat{\gamma}_{T+k-1}, \hat{\gamma}_{T+k-2}, \ldots, \hat{\gamma}_k)$. The accuracy of predictions is based on the average squared forecast error, which is computed as $MSE(\hat{f}_{T+k}) = \hat{\gamma}_0 - \widetilde{\gamma'}_k \hat{V}^{-1} \tilde{\gamma}_k$.

There is a wide diversity of loss functions available and their properties vary extensively. Even so, all of these share a common feature, in that "lower is better." That is, a large value indicates a poor forecasting performance, whereas a value close to zero implies an almost-perfect forecast. We use three average loss indicators: the Mean Absolute Percentage Error (MAPE), the Adjusted Mean Absolute Percentage Error (AMAPE), and the U-statist inequality coefficient.

The MAPE and the AMAPE are relative measures, in that they are percentages. In particular, the MAPE is the percentage error, and has the advantage of having a lower bound of zero. Therefore, the lower the indicator the greater the model's forecast accuracy. Nevertheless, this loss function has drawbacks in any practical application. First, with zero values, we have a division by zero issue. Second, the MAPE does not have an upper limit. The AMAPE corrects almost completely the asymmetry problem between actual forecast values, and has the advantage of having both a zero lower bound and an upper bound. Like the MAPE, the smaller the AMAPE, the greater the accuracy of predictions.

The U-statistic provides a measure of how well a time series of estimated values compares to a corresponding time series of observed values. he Theil inequality coefficient lies between zero and one, with zero suggesting a perfect fit. It can be decomposed into three sources of inequality; bias, variance, and covariance proportions coverage. The bias component of the forecast errors measures the extent to which the mean of the forecast is different from the mean of the recorded values. Similarly, the variance component tells us how far the variation of the forecast is from the variation of the actual series. Finally, the covariance proportion measures the remaining unsystematic component of the forecasting errors. As expected, the three components add up to one.

4. The Basic Empirical Results

4.1 Fractional Integration Analysis

We present in Table 2, the results of the estimations of the $\mathrm{ARFIMA}(\phi, d, \theta)$ models. The best specifications were selected using the Schwartz Bayesian Information Criterion (BIC) and include statistically significant autoregressive and moving-average terms.

We perform preliminary tests for the existence of structural breaks for all variables following the procedures in Bai-Perron (2003). Test results show no significant evidence for break points. Still, when by simple visual inspection of the data we suspected the possible presence of break points, a dummy variable was included in the ARFIMA models. The corresponding estimated coefficients were never statistically significant and the best specification for ARFIMA models as indicated by the BIC never includes structural breaks.

[Insert Table 2 around here]

Our results provide strong empirical evidence for the non-rejection of the presence of long memory for both aggregate CO_2 emissions and each of its five components. The estimated values of the fractional parameter d are all between 0 and 1, thus allowing us to reject both the case of pure stationarity model ($d = 0$) and the case of a unit root model ($d = 1$). Furthermore, all series exhibit long-term memory as all estimated parameters d lie within the interval (0, 0.5).

Total CO_2 emissions have a degree of persistence of d = 0.270. In relative terms, emission from gas flaring show the smallest degree of persistence, d = 0.217, while emissions from coal consumption show the highest degree of persistence, d = 0.471. Furthermore, the degree of persistence we estimate for aggregate emissions corresponds to the convex combination of the five individual results, which attests to the accuracy of our estimates.

With the exception of emissions from gas flaring combustion, all of the estimates of the fractional integration parameter are statistically significant at 1%. For aggregate emissions and emissions from solid fuels and from cement production, the upper bound is slightly greater than 0.5, leaving open the possibility that the different series may be non-stationary, though still mean reverting.

4.2 In-Sample Global CO2 Emissions Forecasts

Figure 1 plots the actual values against the in-sample forecasts for global CO_2 emissions between 1950 and 2017. Table 3 summarizes our in-sample forecasting accuracy results.

[Insert Figure 1, Table 3 around here]

We get excellent in-sample predictions with a MAPE ranging from a minimum of 3.2% for aggregate CO_2 emissions to a maximum of 6.8% for emissions from gas flaring. In addition, the percentage of projected values outside the confidence interval ranges from a minimum of 4.4% for total emissions to a maximum of 7.5% for emissions from gas flaring.

In turn, the U-statistic is very low, varying in a band between 0.01 and 0.05. This suggests that the predictions compare quite well with the observed values. Furthermore, the predictions are non-skewed and show a low variance, which suggests that they closely follow the changes in the observed values. In fact, more than 94% of the prediction error in all components under analysis is non-systematic.

Finally, the projections based on the aggregate results are very close to the sum of the projections for each of its five components. The difference is, on average, 1% for the in-sample projections discussed here and 4.5% for the out-of-sample projections presented below. This confirms the good performance of our ARFIMA approach.

5. ARFIMA CO2 Emissions Forecasts and their Implications

5.1 The ARFIMA Forecasts 2018 - 2050

Having established a good in-sample forecasting performance for the ARFIMA estimates, we use these estimates to forecast CO_2 emissions until 2050. We present the detailed results in Figure 2 and in Tables A1 to A6 in the Appendix. In turn, in Table 4, we present summary results relative to 2010 reference levels.

We forecast total CO_2 emissions to be 37,171 Mt by 2050 after having reached a peak of 37,623 Mt in 2034. The forecasted levels of emissions in 2030 and 2050 are 12.4% and 11.1% above the 2010 reference level, respectively.

[Insert Figure 2 and Table 4 around here]

From a disaggregated perspective, we forecast CO_2 emissions from liquid fuels, gas fuels, and cement production to be systematically above the 2010 reference levels. In turn, we project emissions from solid fuels and from gas flaring to be below the 2010 reference levels after the first few years into the forecasting horizon.

We forecast CO_2 emissions from liquid fuels to be 14.2% and 15.2% above the 2010 emissions levels by 2030 and 2050, respectively. In turn, the projected emissions from gas fuels are 29.9% and 42.2% above the 2010 level by 2030 and 2050, respectively. The same is true for the projected emissions from cement production, which will reach levels 33.0% and 27.4% above the 2010 levels by 2030 and 2050, respectively.

Conversely, projections of CO_2 emissions from solid fuels follow a decreasing pattern from 2021 onwards. By 2030 and 2050, the projected emissions are 12.9% and 24.3% below the 2010 level. In turn, the projected emissions from gas flaring start declining after 2026 and will reach levels 5.8% and 28.7% below the 2010 levels by 2030 and 2050, respectively.

5.2 The ARFIMA Forecasts and the IPCC Special Report 2018 Targets

Table 5 shows the policy efforts required to meet the new IPCC targets as implied by our ARFIMA forecasts. Figure 3 provides a depiction of the two relevant trajectories: the IPCC targets and the ARFIMA forecasts.

[Insert Table 5 and Figure 3 around here]

Under the IPCC targets, global CO2 emissions would have to decrease by 15,050 Mt or 45% of 2010 emissions by 2030 and a further 12,476 Mt, or a further 40.1% of 2010 levels, between 2030 and 2050. Accordingly, the total target accumulated reduction by 2050 corresponds to a reduction of 85.1% in emissions relative to 2010 levels.

Of the greatest importance is the comparison of the IPCC policy CO_2 emissions targets with our ARFIMA reference scenario emissions. Since our forecasts capture the statistical information included in the sample, these forecasts provide the most fundamental reference case forecasts. We use these to assess the net policy effort, compatible with the carbon neutrality in 2050.

In order to meet the IPCC target for 2030 a policy effort is necessary that cuts 57.4% emissions relative to 2010 levels. From these, 12.4% corresponds to the extra effort due to the inertia of the natural CO_2 emissions system. In turn, for the 2050 target to be reached an additional effort of 97.4% of 2010 emissions is required. Therefore, the policy efforts for decarbonization are not just very large. They are also larger than implied by the IPCC targets. They are also frontloaded and in a way that clearly exceeds the frontloading already contemplated in the IPCC targets.

The general pattern described above where the inertia of the emission system increases the policy effort required to achieve IPCC targets also applies to emissions from liquid fuels, gas fuels, and from cement production. The policy efforts to achieve decarbonization by 2050 are 118.3% of 2010 levels for emissions from cement production, 114.9% for emissions from gas fuels, and 99.3% for liquid fuels.

On the other hand, the emissions from solid fuels and flaring gas combustion have a decreasing trend and, therefore, the inertia of the emissions system suggests that the policy efforts needed to promote the decarbonisation of the economy by 2050 are lower than the IPCC goals themselves. In order to achieve the 2050 target, the policy effort for solid fuel emissions is 72% of the 2010 levels while for gas flaring it is 80.1%.

6. Summary, Conclusions, and Policy Implications

This work uses an ARFIMA approach to evaluate the degree of persistence of worldwide CO_2 emissions from solid, liquid, and gas fossil fuel combustion as well as gas flaring and cement production, and to make the corresponding forecasts into 2050. These forecasts, in turn, allow us to assess the policy effort required to meet the IPCC targets.

Our empirical results suggest that CO_2 emissions, both at the aggregate level and for each of its five different components, are fractionally integrated processes. Accordingly, they show long-memory and the effects of shocks tend to dissipate at a slow hyperbolic rate. Emissions from liquid fuels and gas flaring exhibit the weakest degree of long-range dependence while emissions from solid fuels and cement have the strongest.

The long-memory nature of CO_2 emissions implies that any policy shock will have temporary effects albeit longer lasting than suggested in a traditional analysis of stationarity. The mean reversal property, however, implies that the policy effort must be persistent to produce equally persistent effects. This is particularly relevant in the framework of the international strategies for achieving carbon neutrality in 2050 where it will be crucial to promote permanent changes in behavior.

According to our projections, worldwide CO_2 emissions will peak in 2034 and will slowly decline thereafter. Emissions in 2050 will be 11.1% above the 2010 levels. This aggregate pattern is due to the evolution of emissions from liquid fuels and gas. For emissions from combustion of solid fossil fuels, gas flaring, and cement production, we project eventually declining trajectories.

We measure the policy efforts required to decarbonise the world economy as the difference between the reductions of CO_2 emissions required to achieve the nominal IPCC targets and the evolution of emissions as measured by the underling ARFIMA projections. Our results suggest that at the aggregate level, to achieve such policy targets additional deliberate policy efforts are necessary leading to reduction in emissions by 57.4% and of 97.4% of the 2010 levels by 2030 and 2050, respectively. Accordingly, the necessary policy efforts are very sizeable and more so than suggested by the IPCC targets themselves.

At a disaggregated level, our results also suggest that emissions from liquid fuels, gas fuels and cement production will reach levels clearly above the IPCC 2010 reference value. Accordingly, the inertia underlying the natural emissions system will require policy efforts equivalent to 118.3%, 114.9% and 99.3% of 2010 emissions, respectively, in order to achieve the 2050 target. By contrast, for emissions from solid fuels and flaring gas, inertia will reduce the policy effort required by 72.0% and 80.1% of 2010 levels, respectively.

The policy efforts necessary to reach carbon neutrality by 2050 are not only sizeable. They are also frontloaded. Indeed, about 60% of the necessary reductions have to be achieved in the next decade and just 40% over the next two decades. By contrast, the IPCC targets considered in isolation would seem to imply a share of efforts of about 52.9% over the next decade. The policy efforts for reduction in emissions from liquid fuels are at about the aggregate patterns. In turn, policy efforts for gas fuels and cement production are more frontloaded than indicated by aggregate emissions while those from solid fuel and gas flaring are much less frontloaded.

Finally, our results suggest that the policies toward decarbonization of the economy by 2050 be tailored considering the specific characteristics of each one of the different components of total CO2 emissions – both in terms of their magnitude and their trajectory. Given the differences in the inertia of the different types of emissions a one-size fits all approach is not appropriate.

The economic and societal impacts of climate change - on productivity, water resources, transport, energy production and consumption, migration, tourism and leisure, infrastructure, food production capacity, well-being and public health, migration, biodiversity and even political stability - are still far from being fully identified and much less internalized into policy decision making [see Tol (2018)]. Our results contribute to strengthening the need to define and implement transition, adaptation and mitigation policies climate and energy, consistent with the goal of carbon neutrality in 2050, fully aligned with both the goals of the Paris Agreement and the United Nations Sustainable Development Goals. Such policies are urgent, daunting and frontloaded.

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Table 1 – Global CO_2 Emissions from Fossil Fuel Combustion and Cement Production

Worldwide CO_2 Emissions		Average Shares of Total Emissions (%)					
Years	**Mt**	**Years**	**Solid Fuels**	**Liquid Fuels**	**Gas Fuels**	**Cement Production**	**Gas Flaring**
1950	5 972.32	**1950-1959**	60.2	29.7	7.3	1.4	1.5
1960	9 412.82	**1960-1969**	46.9	38.9	10.6	1.9	1.8
1970	14 850.19	**1970-1979**	35.7	47.2	12.9	2.1	2.1
1980	19 422.86	**1980-1989**	39.4	42.1	15.1	2.4	1.0
1990	22 255.14	**1990-1999**	36.9	41.3	18.1	3.0	0.6
2000	24 669.71	**2000-2009**	38.1	38.5	18.7	4.0	0.7
2010	33 444.99	**2010-2017**	41.4	33.6	18.8	5.5	0.7
2017	36 767.15	**2017**	39.6	34.4	19.6	5.7	0.7
1950-2017		**1950-2017**	38.9	37.7	17.9	3.2	1.0

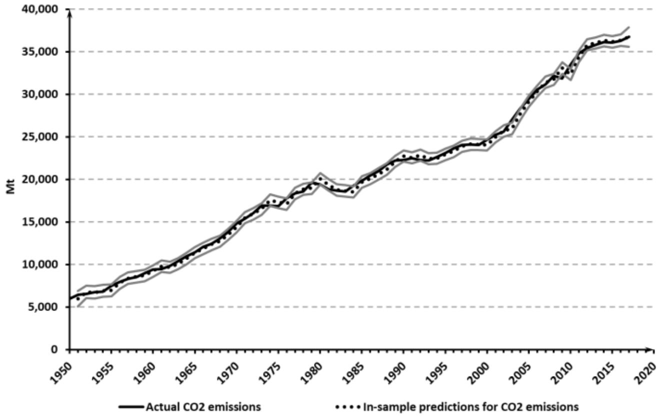
Table 2 – Fractional-Integration Results

Variable	Coefficient	Estimates	Std. Err.	p-value	Significance interval	BIC
Total CO_2 Emissions	α_1	1.640	*0.188*	*0.000*	[1.272 ; 2.008]	*1,044.96*
	α_2	-0.643	*0.187*	*0.001*	[-1.010 ; -0.276]	
	θ_1	-0.512	*0.151*	*0.001*	[-0.808 ; -0.216]	
	θ_6	0.262	*0.126*	*0.038*	[0.015 ; 0.509]	
	d	**0.270**	***0.144***	***0.060***	**[-0.012 ; 0.552]**	
CO_2 Emissions from Solid Fuels	α_1	0.952	*0.031*	*0.000*	[0.891 ; 1.013]	950.35
	θ_7	0.508	*0.178*	*0.004*	[0.159 ; 0.857]	
	d	**0.471**	***0.041***	***0.000***	**[0.391 ; 0.551]**	
CO_2 Emissions from Liquid Fuels	α_1	0.992	*0.010*	*0.000*	[0.972 ; 1.012]	*961.85*
	θ_3	0.249	*0.108*	*0.021*	[0.037 ; 0.461]	
	d	**0.285**	***0.093***	***0.002***	**[0.103 ; 0.467]**	
CO_2 Emissions from Gas Fuels	α_1	0.997	*0.004*	*0.000*	[0.989 ; 1.005]	*829.14*
	α_3	0.123	*0.124*	*0.323*	[-0.120 ; 0.366]	
	d	**0.314**	***0.067***	***0.000***	**[0.183 ; 0.445]**	
CO_2 Emissions from Cement Production	α_1	0.975	*0.018*	*0.000*	[0.940 ; 1.010]	*654.66*
	α_7	0.673	*0.140*	*0.002*	[0.399 ; 0.947]	
	d	**0.470**	***0.040***	***0.000***	**[0.392 ; 0.548]**	
CO_2 Emissions from Gas Flaring	α_1	0.970	*0.032*	*0.000*	[0.907 ; 1.033]	*623.71*
	d	***0.217***	***0.113***	***0.058***	**[-0.004 ; 0.438]**	

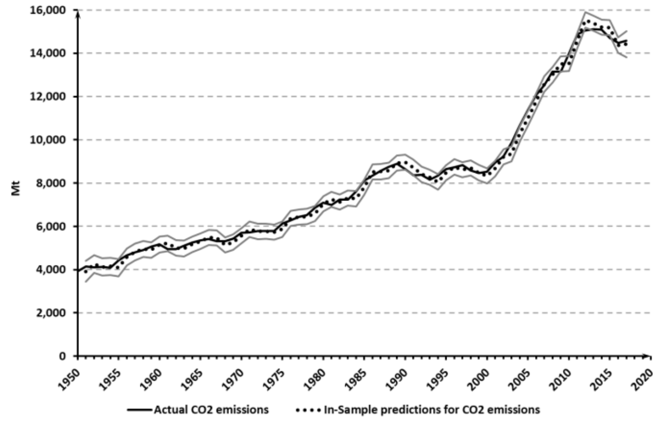
Note: $\hat{\alpha}$ stands for the estimated value of the parameter associated with x_{t-p} of the AR component and $\hat{\theta}$ stands for the estimated value of the stochastic term of order q (e_{t-q}) of the MA component.

Figure 1 - In-Sample CO_2 Predictions: 1950-2017

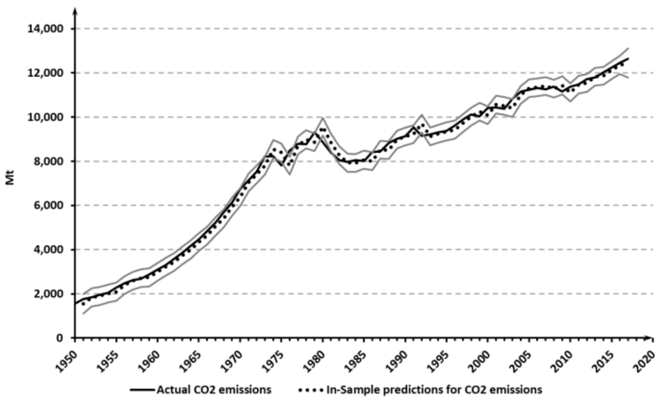
a) Aggregate CO_2 Emissions



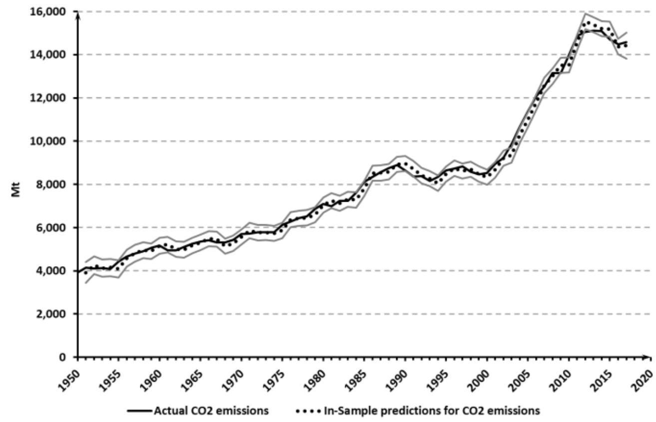
b) CO_2 Emissions from Solid Fuels



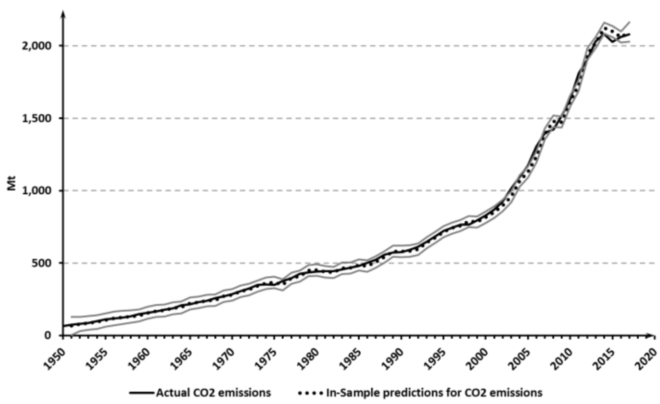
c) CO_2 Emissions from Liquid Fuels



d) CO_2 Emissions from Gas Fuels



e) CO_2 emissions from Cement Production



f) CO_2 Emissions from Gas Flaring

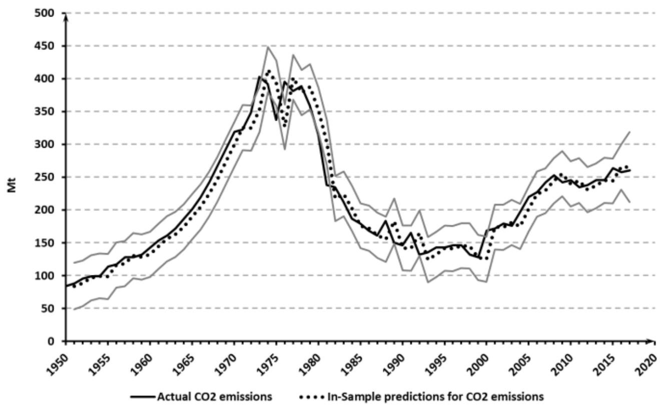


Table 3 - In-Sample Forecasts Accuracy Analysis: 1950-2017

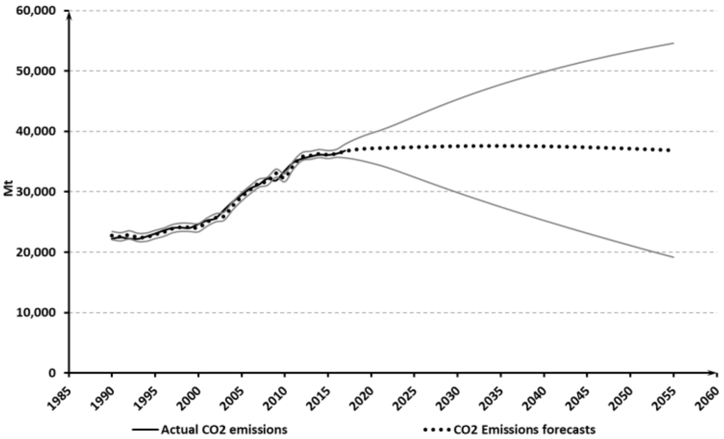
	CO_2 Emissions					
	Aggregate	**Solid Fuels**	**Liquid Fuels**	**Gas Fuels**	**Cement**	**Gas Flaring**
Mean Absolute Percentage Error (MAPE)	3.2%	3.6%	4.2%	3.7%	3.9%	6.8%
Adjusted Mean Absolute Percentage Error (AMAPE)	2.3%	2.5%	2.9%	2.6%	2.7%	3.4%
Theil Inequality Coefficient	0.02	0.03	0.02	0.01	0.01	0.05
Mean Squared Error decomposition:						
Bias proportion	2.0%	0.1%	1.0%	1.4%	2.6%	2.5%
Variance proportion	0.8%	0.0%	1.6%	4.6%	0.2%	0.9%
Covariance proportion	97.2%	99.8%	97.5%	94.1%	97.2%	96.6%

Table 4 – CO_2 Emissions Forecasts Emissions Relative to 2010 Reference Levels (%)

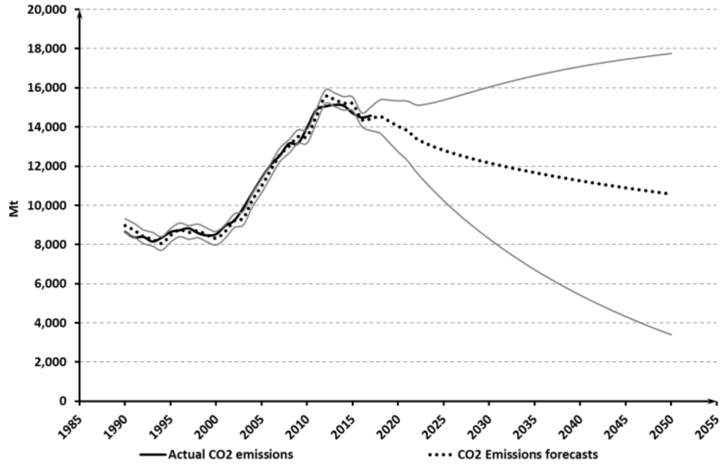
	Aggregate	Solid Fuels	Liquid Fuels	Gas Fuels	Cement	Gas Flaring
2020	11.3	0.5	11.1	19.6	36.6	6.0
2030	12.4	-12.9	14.2	29.9	33.0	-5.8
2040	12.3	-19.4	15.3	36.9	31.1	-17.9
2050	11.1	-24.3	15.2	42.2	27.4	-28.7

Figure 2 – CO_2 Emissions Forecasts for 2018 - 2050

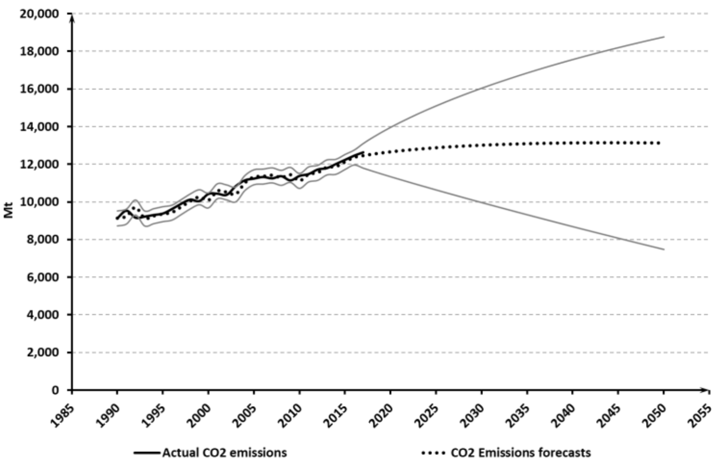
a) Total CO_2 Emissions



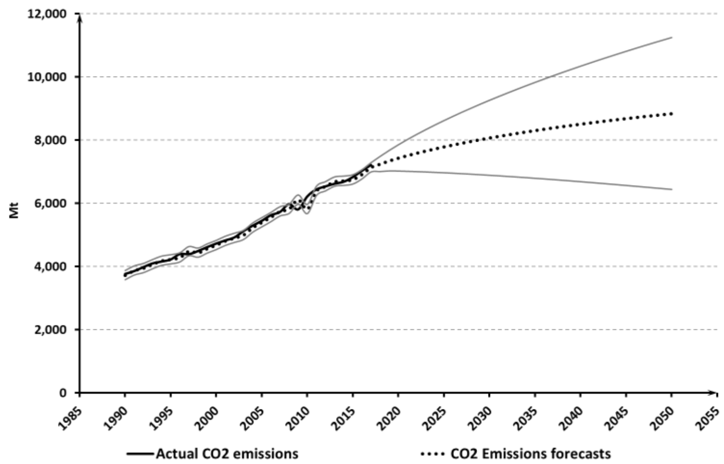
b) CO_2 Emissions from Solid Fuels



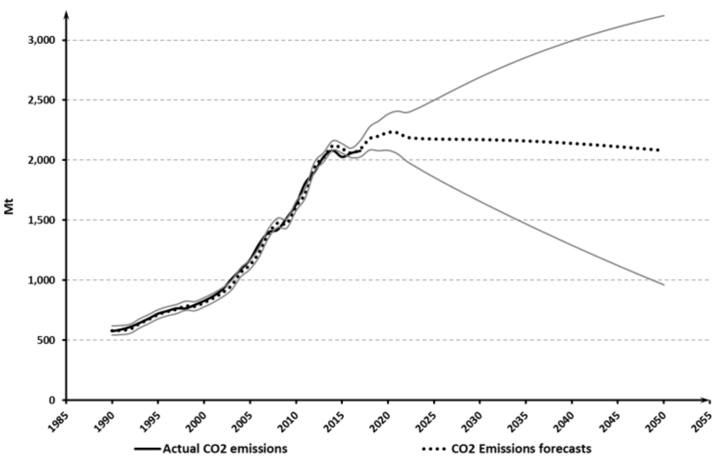
c) CO_2 Emissions from Liquid Fuels



d) CO_2 Emissions from Gas Fuels



e) CO_2 Emissions from Cement Production



f) CO_2 Emissions from Gas Flaring

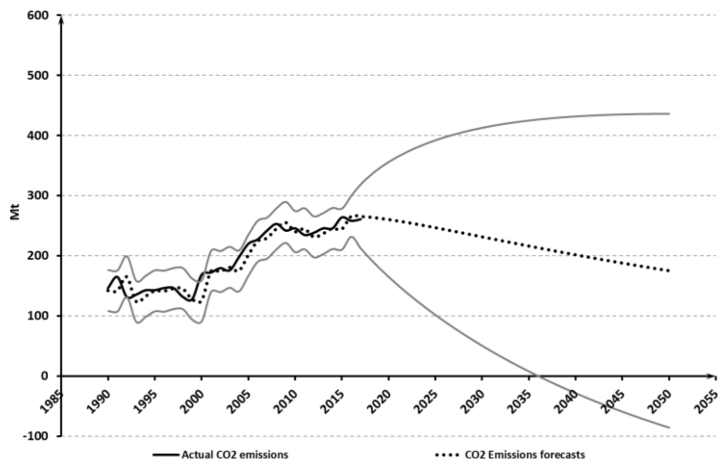
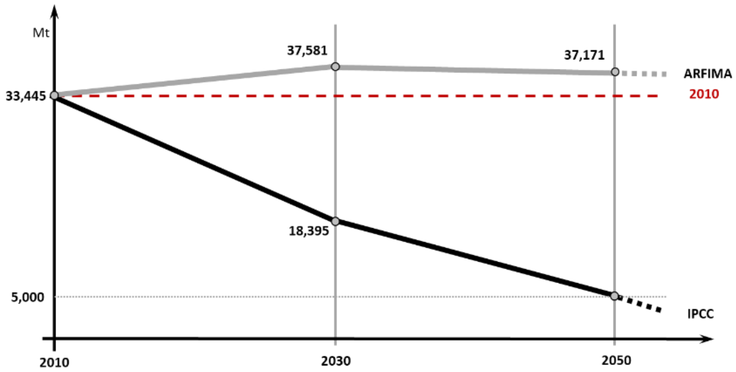


Table 5 - Reductions in CO2 Emissions Relative to 2010 (%)

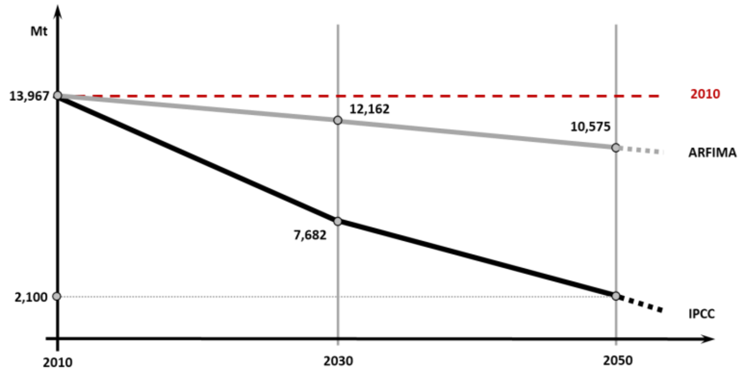
	2030	2050
IPCC (2018) targets	**-45.0**	**-85.1**
Policy effort based on ARFIMA forecasts		
Total	-57.4	-97.4
Solid Fuels	-32.1	-72.0
Liquid Fuels	-59.2	-99.3
Gas Fuels	-74.9	-114.9
Cement Production	-78.0	-118.3
Gas Flaring	-39.2	-80.1

Figure 3 – CO_2 Emissions: ARFIMA Projections versus IPCC Goals

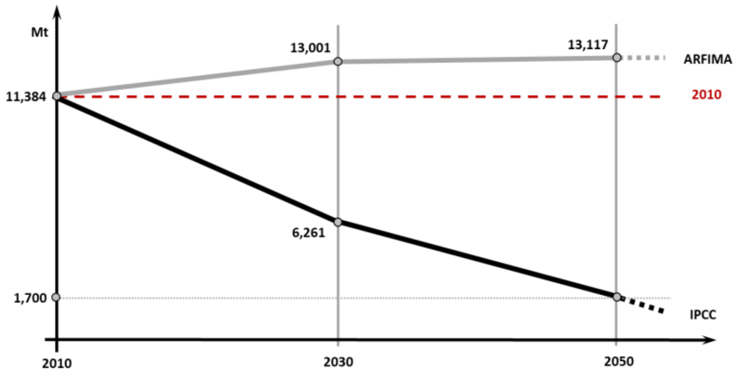
a) Total CO_2 Emissions



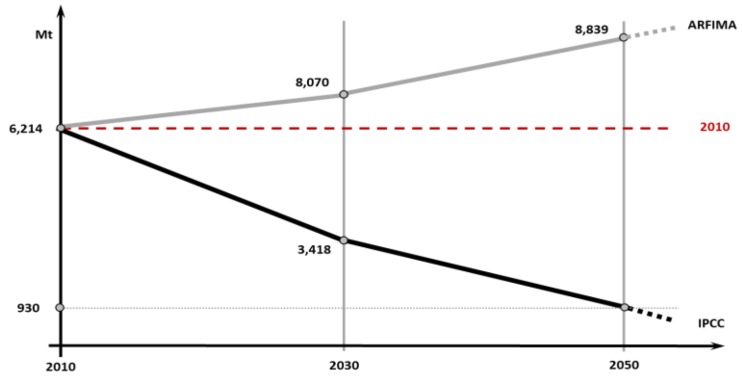
b) CO_2 Emissions from Solid Fuels



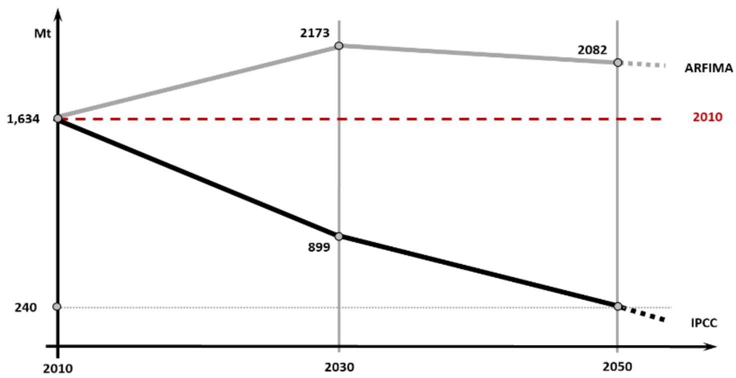
c) CO_2 Emissions from Liquid Fuels



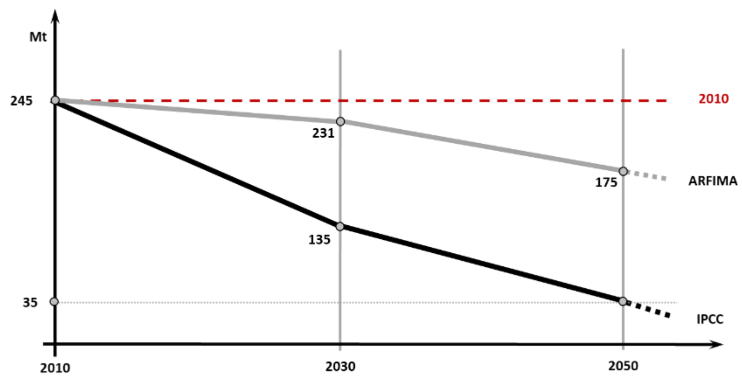
d) CO_2 Emissions from Gas Fuels



e) CO_2 Emissions from Cement Production



f) CO_2 Emissions from Gas Flaring



APPENDIX

Table A1 – Total CO_2 Emissions Forecasts for 2018-2050

Years	Total CO_2 emissions (forecasts - f_t)	Distançe to reference year (2010)	RMSE		Confidence interval (95%)	
			MtCO2	$rmse_t/f_t$ (%)	Lower limit	Upper limit
2018	36,990	10.6	975	2.6	35,387	38,594
2019	37,141	11.1	1,243	3.3	35,096	39,186
2020	37,214	11.3	1,502	4.0	34,743	39,684
2021	37,255	11.4	1,752	4.7	34,374	40,136
2022	37,295	11.5	2,045	5.5	33,931	40,660
2023	37,338	11.6	2,368	6.3	33,442	41,233
2024	37,381	11.8	2,706	7.2	32,930	41,832
2025	37,423	11.9	3,049	8.1	32,408	42,437
2026	37,463	12.0	3,390	9.0	31,886	43,039
2027	37,499	12.1	3,727	9.9	31,369	43,629
2028	37,531	12.2	4,057	10.8	30,857	44,204
2029	37,558	12.3	4,380	11.7	30,353	44,763
2030	37,581	12.4	4,696	12.5	29,857	45,305
2031	37,599	12.4	5,004	13.3	29,368	45,829
2032	37,612	12.5	5,304	14.1	28,887	46,336
2033	37,620	12.5	5,597	14.9	28,413	46,827
2034	37,623	12.5	5,884	15.6	27,945	47,301
2035	37,622	12.5	6,164	16.4	27,483	47,761
2036	37,617	12.5	6,438	17.1	27,028	48,206
2037	37,607	12.4	6,706	17.8	26,577	48,637
2038	37,593	12.4	6,968	18.5	26,132	49,054
2039	37,576	12.4	7,225	19.2	25,692	49,459
2040	37,554	12.3	7,477	19.9	25,257	49,852
2041	37,530	12.2	7,724	20.6	24,826	50,234
2042	37,502	12.1	7,966	21.2	24,399	50,604
2043	37,470	12.0	8,204	21.9	23,976	50,964
2044	37,436	11.9	8,437	22.5	23,557	51,314
2045	37,398	11.8	8,667	23.2	23,142	51,654
2046	37,358	11.7	8,893	23.8	22,731	51,985
2047	37,315	11.6	9,114	24.4	22,323	52,307
2048	37,270	11.4	9,332	25.0	21,919	52,620
2049	37,222	11.3	9,547	25.6	21,518	52,925
2050	37,171	11.1	9,758	26.3	21,121	53,222

Table A2 – CO_2 Emissions from Solid Fuels Forecasts for 2018-2050

Years	Total CO_2 emissions forecasts (f_t) (Mt)	Distançe to reference year: 2010 (%)	RMSE		Confidence interval (95%)	
			MtCO2	$rmse_t/f_t$ (%)	Lower limit	Upper limit
2018	14,533	4.0	520	3.6	13,677	15,388
2019	14,293	2.3	661	4.6	13,206	15,381
2020	14,031	0.5	796	5.7	12,722	15,340
2021	13,808	-1.1	924	6.7	12,288	15,327
2022	13,406	-4.0	1,046	7.8	11,685	15,127
2023	13,166	-5.7	1,215	9.2	11,168	15,163
2024	12,973	-7.1	1,391	10.7	10,686	15,260
2025	12,806	-8.3	1,565	12.2	10,231	15,381
2026	12,657	-9.4	1,736	13.7	9,802	15,512
2027	12,520	-10.4	1,901	15.2	9,394	15,647
2028	12,393	-11.3	2,060	16.6	9,005	15,782
2029	12,274	-12.1	2,213	18.0	8,634	15,914
2030	12,161	-12.9	2,360	19.4	8,280	16,043
2031	12,054	-13.7	2,501	20.8	7,940	16,168
2032	11,952	-14.4	2,637	22.1	7,614	16,289
2033	11,853	-15.1	2,767	23.3	7,301	16,405
2034	11,758	-15.8	2,893	24.6	7,000	16,517
2035	11,667	-16.5	3,013	25.8	6,711	16,623
2036	11,579	-17.1	3,129	27.0	6,432	16,726
2037	11,493	-17.7	3,240	28.2	6,163	16,823
2038	11,410	-18.3	3,348	29.3	5,904	16,917
2039	11,330	-18.9	3,451	30.5	5,654	17,006
2040	11,252	-19.4	3,550	31.6	5,413	17,091
2041	11,176	-20.0	3,646	32.6	5,179	17,172
2042	11,102	-20.5	3,738	33.7	4,954	17,250
2043	11,030	-21.0	3,827	34.7	4,736	17,324
2044	10,960	-21.5	3,912	35.7	4,525	17,395
2045	10,892	-22.0	3,995	36.7	4,321	17,462
2046	10,825	-22.5	4,074	37.6	4,123	17,527
2047	10,760	-23.0	4,151	38.6	3,932	17,588
2048	10,697	-23.4	4,226	39.5	3,747	17,647
2049	10,635	-23.9	4,297	40.4	3,567	17,704
2050	10,575	-24.3	4,367	41.3	3,393	17,757

Table A3 – CO_2 Emissions from Liquid Fuels Forecasts for 2018-2050

Years	Total CO_2 emissions forecasts (f_t) (Mt)	Distançe to reference year: 2010 (%)	RMSE		Confidence interval (95%)	
			MtCO2	$rmse_t/f_t$ (%)	Lower limit	Upper limit
2018	12,524	10.0	544	4.3	11,629	13,419
2019	12,590	10.6	676	5.4	11,478	13,702
2020	12,649	11.1	801	6.3	11,332	13,967
2021	12,702	11.6	921	7.2	11,187	14,217
2022	12,750	12.0	1,036	8.1	11,045	14,454
2023	12,792	12.4	1,147	9.0	10,905	14,680
2024	12,831	12.7	1,255	9.8	10,767	14,896
2025	12,867	13.0	1,360	10.6	10,629	15,105
2026	12,899	13.3	1,463	11.3	10,493	15,305
2027	12,929	13.6	1,563	12.1	10,358	15,499
2028	12,955	13.8	1,660	12.8	10,224	15,686
2029	12,980	14.0	1,756	13.5	10,091	15,868
2030	13,001	14.2	1,850	14.2	9,959	16,044
2031	13,021	14.4	1,941	14.9	9,828	16,214
2032	13,039	14.5	2,031	15.6	9,698	16,380
2033	13,055	14.7	2,120	16.2	9,568	16,542
2034	13,069	14.8	2,207	16.9	9,439	16,699
2035	13,082	14.9	2,292	17.5	9,311	16,852
2036	13,093	15.0	2,376	18.2	9,184	17,001
2037	13,102	15.1	2,459	18.8	9,057	17,147
2038	13,110	15.2	2,541	19.4	8,931	17,289
2039	13,117	15.2	2,621	20.0	8,806	17,428
2040	13,122	15.3	2,700	20.6	8,681	17,563
2041	13,126	15.3	2,778	21.2	8,557	17,695
2042	13,129	15.3	2,855	21.7	8,434	17,825
2043	13,131	15.3	2,930	22.3	8,311	17,951
2044	13,132	15.4	3,005	22.9	8,189	18,075
2045	13,132	15.4	3,079	23.4	8,068	18,196
2046	13,131	15.3	3,151	24.0	7,947	18,314
2047	13,128	15.3	3,223	24.6	7,826	18,430
2048	13,125	15.3	3,294	25.1	7,707	18,544
2049	13,121	15.3	3,364	25.6	7,588	18,655
2050	13,117	15.2	3,433	26.2	7,469	18,764

Table A4 – CO_2 Emissions from Gas Forecasts for 2018-2050

Years	Total CO_2 emissions forecasts (f_t) (Mt)	Distançe to reference year: 2010 (%)	RMSE		Confidence interval (95%)	
			MtCO2	$rmse_t/f_t$ (%)	Lower limit	Upper limit
2018	7,242	16.5	145	2.0	7,003	7,481
2019	7,346	18.2	197	2.7	7,022	7,670
2020	7,433	19.6	253	3.4	7,017	7,848
2021	7,513	20.9	306	4.1	7,010	8,016
2022	7,587	22.1	357	4.7	7,000	8,175
2023	7,658	23.2	407	5.3	6,989	8,326
2024	7,724	24.3	455	5.9	6,977	8,472
2025	7,788	25.3	501	6.4	6,964	8,613
2026	7,849	26.3	547	7.0	6,950	8,749
2027	7,908	27.3	592	7.5	6,935	8,881
2028	7,964	28.2	635	8.0	6,919	9,009
2029	8,018	29.0	678	8.5	6,902	9,133
2030	8,070	29.9	720	8.9	6,885	9,255
2031	8,120	30.7	762	9.4	6,867	9,373
2032	8,169	31.5	803	9.8	6,849	9,489
2033	8,216	32.2	843	10.3	6,829	9,603
2034	8,262	32.9	883	10.7	6,810	9,713
2035	8,306	33.7	922	11.1	6,790	9,822
2036	8,349	34.3	960	11.5	6,769	9,929
2037	8,390	35.0	999	11.9	6,748	10,033
2038	8,431	35.7	1,036	12.3	6,726	10,136
2039	8,470	36.3	1,074	12.7	6,704	10,236
2040	8,508	36.9	1,111	13.1	6,681	10,335
2041	8,545	37.5	1,147	13.4	6,658	10,432
2042	8,581	38.1	1,183	13.8	6,635	10,528
2043	8,617	38.7	1,219	14.1	6,611	10,622
2044	8,651	39.2	1,255	14.5	6,587	10,715
2045	8,684	39.8	1,290	14.9	6,563	10,806
2046	8,717	40.3	1,325	15.2	6,538	10,896
2047	8,749	40.8	1,359	15.5	6,513	10,984
2048	8,779	41.3	1,393	15.9	6,488	11,071
2049	8,810	41.8	1,427	16.2	6,462	11,157
2050	8,839	42.2	1,461	16.5	6,436	11,242

Table A5 – CO_2 Emissions from Cement Production Forecasts for 2018-2050

Years	Total CO_2 emissions forecasts (f_t) (Mt)	Distançe to reference year: 2010 (%)	RMSE		Confidence interval (95%)	
			MtCO2	$rmse_t/f_t$ (%)	Lower limit	Upper limit
2018	2,181	33.5	59	2.7	2,085	2,278
2019	2,203	34.8	75	3.4	2,079	2,327
2020	2,233	36.6	91	4.1	2,082	2,383
2021	2,231	36.5	107	4.8	2,054	2,407
2022	2,194	34.3	123	5.6	1,992	2,396
2023	2,184	33.7	145	6.7	1,945	2,423
2024	2,180	33.4	170	7.8	1,900	2,460
2025	2,178	33.3	195	8.9	1,857	2,499
2026	2,177	33.2	220	10.1	1,816	2,538
2027	2,176	33.2	244	11.2	1,775	2,578
2028	2,175	33.1	268	12.3	1,735	2,616
2029	2,174	33.1	291	13.4	1,695	2,654
2030	2,173	33.0	314	14.5	1,656	2,690
2031	2,172	32.9	337	15.5	1,618	2,726
2032	2,170	32.8	359	16.5	1,580	2,760
2033	2,168	32.6	380	17.5	1,542	2,793
2034	2,165	32.5	401	18.5	1,505	2,825
2035	2,162	32.3	422	19.5	1,468	2,855
2036	2,159	32.1	442	20.5	1,432	2,885
2037	2,155	31.9	461	21.4	1,396	2,914
2038	2,151	31.6	481	22.3	1,360	2,941
2039	2,146	31.3	499	23.3	1,325	2,968
2040	2,142	31.1	518	24.2	1,290	2,993
2041	2,137	30.8	536	25.1	1,255	3,018
2042	2,131	30.4	553	26.0	1,221	3,042
2043	2,126	30.1	571	26.8	1,187	3,065
2044	2,120	29.7	588	27.7	1,154	3,087
2045	2,114	29.4	604	28.6	1,121	3,108
2046	2,108	29.0	620	29.4	1,088	3,128
2047	2,102	28.6	636	30.3	1,056	3,148
2048	2,095	28.2	652	31.1	1,023	3,167
2049	2,089	27.8	667	31.9	992	3,186
2050	2,082	27.4	682	32.7	960	3,203

Table A6 – CO_2 Emissions from Gas Flaring Forecasts for 2018-2050

Years	Total CO_2 emissions forecasts (f_t) (Mt)	Distançe to reference year: 2010 (%)	RMSE		Confidence interval (95%)	
			MtCO2	$rmse_t/f_t$ (%)	Lower limit	Upper limit
2018	264.0	7.6	42.1	15.9	195	333
2019	262.3	6.8	50.6	19.3	179	345
2020	260.1	6.0	58.2	22.4	164	356
2021	257.7	5.0	65.2	25.3	150	365
2022	255.1	3.9	71.6	28.1	137	373
2023	252.4	2.8	77.6	30.8	125	380
2024	249.5	1.6	83.2	33.3	113	386
2025	246.6	0.5	88.4	35.8	101	392
2026	243.6	-0.8	93.3	38.3	90	397
2027	240.6	-2.0	97.9	40.7	80	402
2028	237.5	-3.2	102.2	43.0	69	406
2029	234.4	-4.5	106.3	45.3	60	409
2030	231.4	-5.8	110	47.6	50	413
2031	228.3	-7.0	114	49.9	41	416
2032	225.2	-8.3	117	52.1	32	418
2033	222.2	-9.5	121	54.3	24	421
2034	219.1	-10.7	124	56.5	15	423
2035	216.1	-12.0	127	58.7	7	425
2036	213.1	-13.2	130	60.9	0	426
2037	210.2	-14.4	132	63.0	-8	428
2038	207.2	-15.6	135	65.2	-15	429
2039	204.3	-16.8	138	67.3	-22	431
2040	201.5	-17.9	140	69.4	-29	432
2041	198.7	-19.1	142	71.5	-35	432
2042	195.9	-20.2	144	73.7	-41	433
2043	193.1	-21.3	146	75.8	-48	434
2044	190.4	-22.4	148	77.9	-54	434
2045	187.8	-23.5	150	80.0	-59	435
2046	185.1	-24.6	152	82.1	-65	435
2047	182.6	-25.6	154	84.2	-70	436
2048	180.0	-26.7	155	86.3	-76	436
2049	177.5	-27.7	157	88.5	-81	436
2050	175.1	-28.7	159	90.6	-86	436

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