# In Sum, Nations Will Likely Fulfill Their Pledges to Reduce Greenhouse Gas Emissions: A Stock-and-Flow-Based View

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## Abstract

*Emission reduction pledges of almost all UN member states, intended nationally determined contributions (INDCs), were signed in December 2015. If they are met, world temperature will stabilize at about 3°C warmer than pre-industrial levels. But will they be met? Commonly, business-as-usual scenarios predict 5–6°C warming and limiting warming to 3°C is regarded to be an arduous task. We however find that achieving the 3°C warming indeed results from business-as-usual past trends in energy investments. Using a stock-and-flow framework for estimating average energy capacity additions for five regions of the world, we conclude that extrapolation past investment trends also gives a 3°C warming, implying that, in sum, INDCs will likely be met. But limiting warming to 3°C is clearly not enough: We use the same stock-and-flow model to show that a combination of increased energy efficiency, facing out all fossil investments before 2030 and implementation of carbon capture and storage is required to limit global warming to 2°C.*

## Background

Limiting climate change will be key to future human wellbeing. The COP21 agreement achieved in Paris in 2015 (Paris Agreement, 2015) and about to be signed by most UN member states in 2016 is good. On the one hand, nations pledge to reduce their emissions, but on the other hand pledges implied by the INDCs (intended nationally determined contributions), covering mainly the 2015-2030 period, will only ensure that the global temperature rise is limited to 2.7°C (CI, 2015) or 3.5°C (CAT, 2015) above pre-industrial temperatures, depending on post-2030 assumptions. On the other hand, the final COP21 document reflects that the pledges are far from sufficient, and in order for global warming to stop before 2°C, parties must later meet to further tighten their INDCs.

Analyses of likely future temperature rises, assuming no new policies, are yet far bleaker. Current energy and related greenhouse gas (GHG) inertias imply far higher emissions than those implied by nation’s pledges: Emissions are consistent with a 5–6°C (IPCC, 2014; IEA, 2015) future. If so, limiting warming to 2.7–3.5°C will be extremely challenging. Achieving, as the COP21 final agreement text states, a world where emissions are cut in line with a 2°C warming will be almost impossible.

Yet other voices (Stern et al, 2016) note that some countries like China, which is currently responsible for about 1/3 of global GHG emissions, may already have seen its GHG emission peak. Stern et al. claim that China will not only meet, but significantly overachieve its INDC pledge of peaking GHG emissions before 2030. Their arguments hinge mostly on two strong trends that they find already well established, and that the newly agreed upon Chinese five-year plan further bolstered: The Chinese are embarking on a transformation from an industrial to a service economy. Its GDP growth will thus be tempered. Additionally, the authors find a strong transition from fossil to renewable energy sources.

This paper probes further into this inertia question, and addresses whether current policies in place will lead us to a 3°C world. The difference has major implications on both the likelihood of achieving the INDCs and thus how draconian measures will have to be to meet the demands of a lively future planet Earth.

We first present other business-as-usual scenarios and compare them with our understanding of business-as-usual. Then, by comparing our results instead with INDC scenarios, we establish that our business-as-usual scenario is actually in agreement with the path suggested by INDCs. At the end, we present a modified version of our approach to demonstrate what is necessary to limit global warming to 2°C.

## Business as usual

The term "business as usual" may be interpreted in a number of different ways. In the context of climate change, the interpretation may vary from assuming no change in energy mix, no change in the current energy intensity of the economy and/or continued economic growth at current levels, to a softer interpretation that there will not be major changes in policies while allowing current trends in technology, society and economy to continue. In this section, we interpret two widely accepted business-as-usual scenarios.

### *IPCC*

For decades, the Intergovernmental Panel on Climate Change (IPCC) has issued reports on various pathways that the world might follow in terms of GHG emissions and their temperature consequences (IPCC, 2014). IPCC uses one classification as Business As Usual (BAU). Though clearly not defined as a likely future emissions pathway, its Representative Climate Pathway (RCP) 8.5 is a reference, attempting to capture future emissions if inertias reflected in current GHG related policies continue. RCP 8.5 is described in Riahi et al. (2011), and uses IIASA Integrated Assessment Modeling Framework. RCP 8.5 is characterized by rapid population growth accompanied by a slow per-capita income growth, limited technology growth, and hence slow improvement in energy intensity. High energy demand, accompanied by a fragmented geopolitical scene, slow economic and technological growth creates an energy supply highly dependent on fossil fuels (Riahi et al. 2011).

This pathway implies that GHG emissions will more than double from current levels of about 50 $GtCO_2$/year to about 100 $GtCO_2$/year as they flatten out 100 years from now. How the climate will handle such $CO_2$ atmospheric concentrations is uncertain but the global temperature rise will continue to rise from a level of about 5°C mid next century. For simplicity, we call this a 6°C world.

**Table 1: The bottom RCP 8.5 is the IPCC BAU, where temperature will continue to increase even after 2100 and probably not stop before 6°C (IPCC, 2014).**

| $CO_2$-eq concentrations in 2100 [ppm $CO_2$eq] | Subcategories | Relative position of the RCPs | Cumulative $CO_2$ emissions [$GtCO_2$] | | Change in $CO_2$eq emissions compared to 2010 [%] | | Temperature change (relative to 1850–1900) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2011–2050 | 2011–2050 | 2050 | 2100 | 2100 Temperature change [°C] | Likelihood of staying below temperature level over the 21st century | | | |
| | | | | | | | | 1.5°C | 2.0°C | 3.0°C | 4.0°C |
| >1000 | Total range | RCP8.5 | 1840–2210 | 5350–7010 | 52 to 95 | 74 to 178 | 4.1–4.8 (2.8–7.8) | | Unlikely | Unlikely | More unlikely than likely |

Figure 1 below shows corresponding GHG emissions form the RCP 8.5. The BAU increase is from 50 $GtCO_2$-eq in 2013 to 65 by 2030, or 30 %.

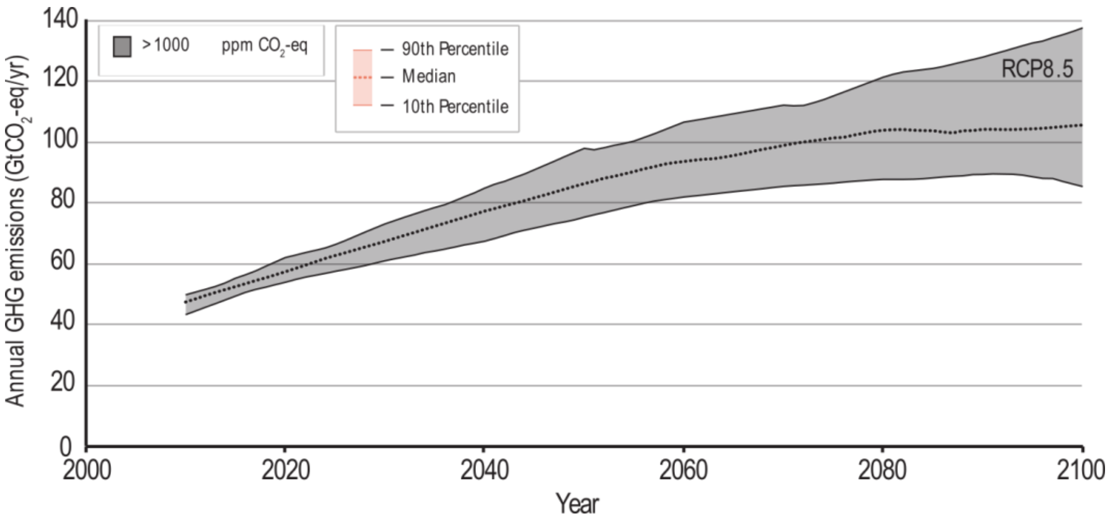


**Figure 1: GHG emissions from the RCP 8.5 (IPCC, 2014)**

## *IEA*

The International Energy Agency (IEA) annually issues its World Energy Outlook (IEA, 2015), where three future scenarios are covered in some detail. CPS (Current Policies Scenario) is the IEA's business-as-usual scenario. The Current Policies Scenario purports to "take into consideration only those policies for which implementing measures had been formally adopted and make the assumption that these policies persist unchanged".

By 2030, emission increase to 39.1 $GtCO_2$ from 31.6 in 2013 (energy system related), or 24% (our linear interpolation between 2020 and 2040, to achieve 2030 figures, as 2030 is not mentioned in their analysis). The scenario is not defined beyond 2040, but there is no indication of GHG emissions plateauing. Though the GHG growth rate is lower than IPCC's, our assumption is that the CPS will also plateau in about 100 years at a level slightly below RCP 8.5, i.e. with a temperature of about 5°C above the 1850–1900 average.

***Ours***

We interpret business as usual in line with Forrester (1961), that the underlying decision making is not changed. Forrester noted that a system's flows capture its decision making. If the information sources remain unchanged, and use of these sources (as captured by the equations using the information sources, frequently referred to as decision rules) do not change, System Dynamics tradition would define decision rules as business as usual: business as usual implies constancy of decision rules.

Our interest is in the future behavior of world GHG emissions, notably the most important part of this, the fossil energy's. We conceptualize this as the stocks of various energy sources capacity to burn fossil fuels. An energy capacity burning stock is depleted mainly by capital decay, and replenished by (gross) capacity additions. A reasonable good source of most nations' energy consumption is BP's database (BP, 2015), complemented by IEA estimates capital life times for various energy assets. Thus our method is captured in Figure 2 below: As we know the historical energy consumption pattern, and capital lifetimes, we can synthesize what the capacity addition must have been. Details of the calculations are presented in Appendix 1.

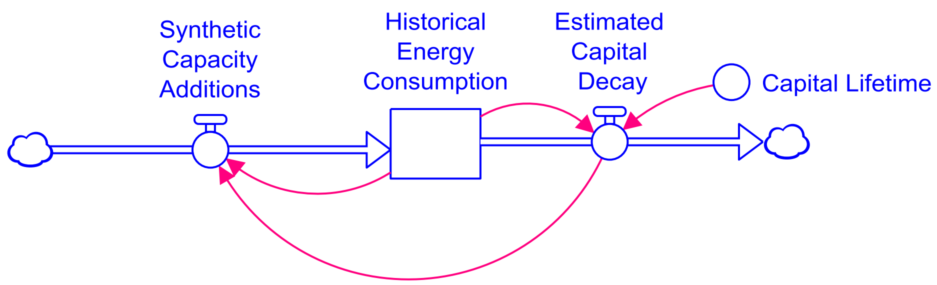


**Figure 2: Synthesizing the flow: capacity additions**

We divide the world into five representative regions of various economic development classes, in line with the classification used by Randers (2011) (USA, China, rest of OECD, emerging economies: BRISE, rest of the world) and estimate capacity additions flows over the last 13 years in the eight major energy carriers (coal, oil, gas, nuclear, hydro, solar, wind and biomass). The synthetic capacity additions are then analyzed to establish whether there was any continuity. We first note that the BP data on consumption, in fact, mixes two aspects of energy use,

1. The capacity to use energy,

2. Utilization of this capacity.

Our interest is mostly in the former. Therefore, we assume that capacity utilization will be constant over time (a reasonable assumption over long time horizon, considering e.g. for hydropower, one year of little water in the hydropower dams is followed by more water and thus hydro energy consumption the next). Smoothing by using a running average of our annual synthetic capacity additions is thus performed. Based on historical smoothed flow patterns, we distinguish three different trend types of capacity additions: Linear-, quadratic- and exponential growth. We test all three trend fits to the flow data series in question and choose whatever trend fits the data best, with some exceptions where we added our judgment—see Appendix 1. An example is presented in Figure 3. Types and parameter of trend fits for all regions and energy carriers are presented in Appendix 1.

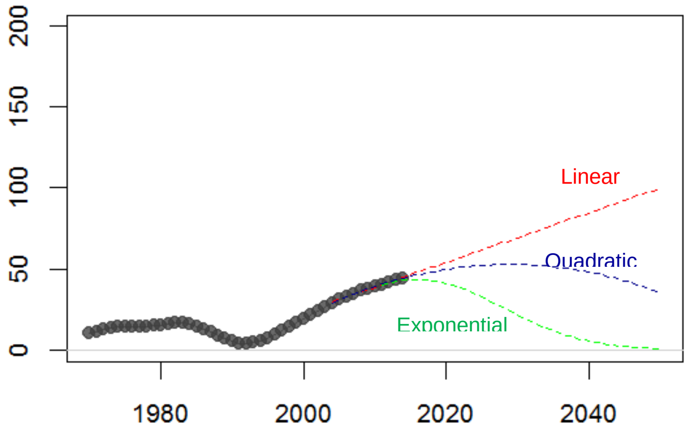


**Figure 3. An example trend analysis for coal capacity additions for BRISE countries. In this case best fit was quadratic trend.**

Figure 4 shows how we first smooth the Synthetic Capacity Additions, and next how we establish Historic Capacity Additions Trends and apply these into the future as Trend Based Capacity Additions. Detailed description of the method is also relegated to Appendix 1.

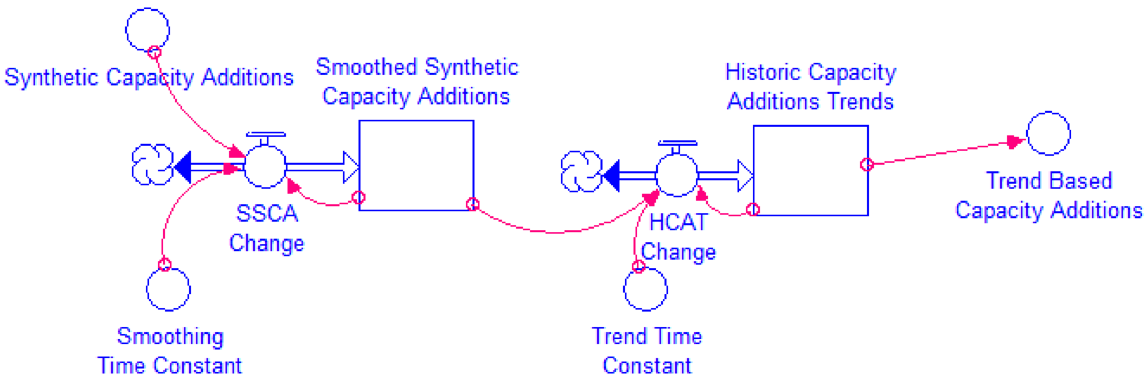

**Figure 4: Trend Based Capacity Additions captures the inertia of past decision making.**

The formulation captured in Figure 4 deviates somewhat from the common System Dynamics formulations inasmuch as the decision maker is absent; there is no representation of someone who operates on basis of stocks and flows surrounding him/her. We still think our approach captures another typical feature of System Dynamics, namely, decision inertia: Instead of establishing how the myriad of public and private investors react to multitude of signals—such as expectation of future profit levels for various investments or emissions reduction ambitions—we simply integrate all such factors into the experienced inertia of investment behavior, i.e. capacity additions.

*Will the future be like the past?*

The analysis further below assumes that business as usual implies that the past is a good predictor of the future. But will the history repeat itself in terms of energy trends? If this historical period can be regarded as an anomaly, then business during the period in question was *not* usual.

However, during the 2000–2013 time period, which forms the basis for our trends, the world saw a representative period of economic ups and downs. It included the 2000–2007 strong global GDP growth and high energy prices, the financial crisis 2007–2010 and extremely low energy prices, again followed by higher prices at the end of the period towards 2013. The entire period was one with significant renewable energy subsidies, but also of even more fossil subsidies.  We believe that the next 15 years both renewables and fossils subsidies will change, but neither will disappear, and globally they will have a similar effect in the next 15 years as they had in the previous 15.

*Applying past flow trends to the future*

We extrapolate the trends established above from 2015 through 2030, thus establishing energy supplies for five regions and eight energy carriers. However, these trends are not directly used to determine energy use by source. In order to make sure that the sum of these trends is in line with future energy demand, we first forecast regional energy demand using determinants of energy demand, and then adjust the trends so that sum of energy capacities is equal to the energy demand. To establish total energy demand, we use the first three terms of the Kaya identity (Kaya and Keiichi, 1997),

$$F = P \times \frac{G}{P} \times \frac{E}{G} \times \frac{F}{E} \qquad (1)$$

where $F$ is $CO_2$ emissions from human sources, $P$ is population, $G$ is GDP, $E$ is energy demand. The terms $G/P$, $E/G$, $F/E$ correspond to GDP per capita (productivity), energy intensity of economy, and emission intensity of energy use, respectively. For each of the five regions, we decompose total energy demand in three components (population, productivity and energy intensity) and separately estimate each component.

$$E = E_{US} + E_{China} + E_{OECD} + E_{BRISE} + E_{ROW} \quad (2)$$

$$E_r = P_r \times \frac{G_r}{P_r} \times \frac{E_r}{G_r} \quad (3)$$

where *r* denotes the region.

Each of the components of Equation 3 is forecast by establishing first a history of the change rate of the corresponding variable at the regional scale, and establishing a trend. The details of these forecasts are beyond the scope of this paper. The final regional forecasts for population, productivity and energy intensity are presented in Appendix 2.

We use the following procedure to calculate the energy supply and $CO_2$ emissions by eight energy carriers:

1. Establish total energy demand, using Equation 3
2. Run the System Dynamics model presented in Figure 4 separately for each of the five regions, using the following built-in decision rules,
    a. Establish future energy supply based on the capacity additions trends, separately for each of the eight energy carriers
    b. In case of regional oversupply: Force retire oil, coal and gas capacities to establish balance
    c. In case of regional shortfall: Add renewable capacity in trend's proportions (This decision rule was never applied, as shortfall never occurred in any region)
3. Using Equation 1, calculate $CO_2$ emissions using Energy Supply and emission intensities of energy sources, available from literature.

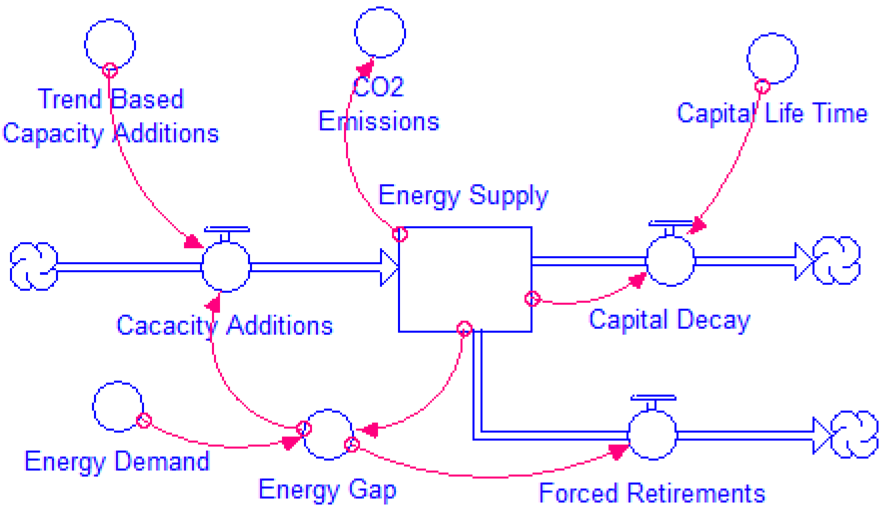


**Figure 5: Establishing energy surplus and shortfalls.**

Figure 5 reflects an anchoring and adjustment decision rule. The anchor is the inertia of past trends, the adjustment occurs when these trends produce energy shortfalls or surpluses. If so, surplus is removed through shutting down of the coal power plants (at that time, they will also be the least profitable), shortfalls will be handled by adding non-fossil capacity, as these are also the least costly.

**What will be the GHG emissions consequences of business as usual?**

Figure 6 presents the resulting $CO_2$ emissions for the "Trends" scenario that includes energy-related emissions as well as constant 6 $GtCO_2$/yr to account for cement production, land use change and forestry emissions.

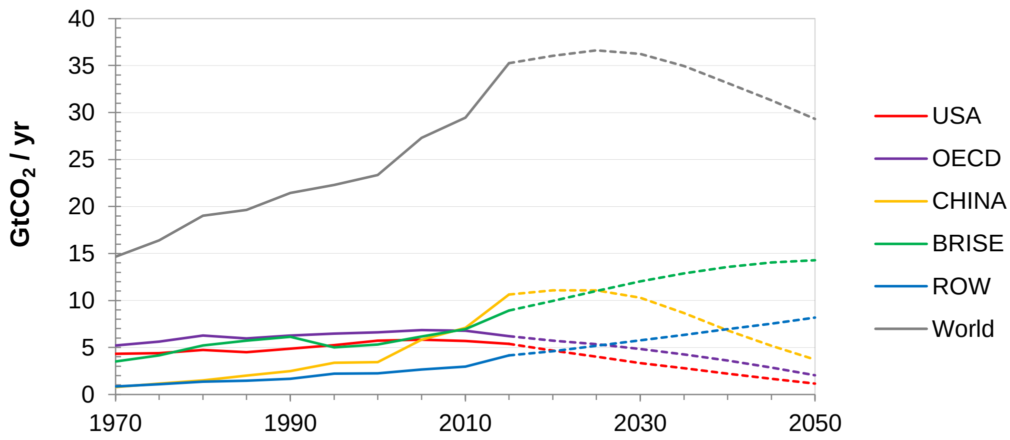


**Figure 6: $CO_2$ emissions under "Trends" scenario.**

In Table 2, we compare our business-as-usual projections with others'.

**Table 2: Our business-as-usual scenario, "Trends", against others'.**

| Scenario | Emission types covered | 2015 – 2030 global growth | Remarks |
|---|---|---|---|
| "Trends" | $CO_2$ emissions | 5 % | Energy (+ cement, land use change and forestry emissions at current level) |
| IEA Current Policies Scenario (CPS) | $CO_2$ energy related emissions | 24 % | |
| IPCC RCP 8.5 | All GHG emissions | 30 % | |

As seen in figure 6, "Trends" emissions will peak within the next 15 years. The IPCC RCP 8.5 is defined for another hundred years, and emissions will not peak within that time horizon. IEA CPS is only defined through 2040, but at that point still shows strong emissions growth.

## What will be the global consequences of INDCs?

### *Business as usual will deliver global INDCs*

We have shown that "Trends" result in far less emissions than the other business-as-usual scenarios. We now investigate whether it creates emissions that align with the INDCs. One major problem with the INDCs is the difficulty to translate the descriptions into consistent and reliable emission pathways. This is either because nations did not make clear what methodology they use in calculating their base emissions and targets, or because some pledges are only qualitative in nature. To address this problem, we use three independent analyses of the effects of INDCs on GHG emissions, done by Climate Interactive (2015), Climate Action Tracker (2015), and IEA (2015) in their most recent "New Policies Scenario" (NPS). They differ, in as much as IEA only looks at energy-related $CO_2$ emissions, Climate Action Tracker only looks at $CO_2$ emissions (including also non-energy ones) and Climate Interactive looks at all GHG emissions, converted into $CO_2$ equivalents. Currently, energy $CO_2$ emissions are about ¾ of all $CO_2$ emissions. $CO_2$ constitutes about ¾ of total GHG emissions. Our "Trends" business-as-usual scenario (similar to Climate Action Tracker), is compared these INDC scenarios in Table 3 showing total emissions growth 2015–2030.

**Table 3: GHG emissions growth 2015–2030**

| Reference | Emission types covered | 2015 – 2030 global growth | Remarks |
|---|---|---|---|
| "Trends" | $CO_2$ emissions | 5 % | Energy + (current level cement + LUCF) |
| IEA New Policies Scenario | $CO_2$ energy related emissions | 9 % | |
| Climate Interactive INDC | All GHG emissions | 0 % | |
| Climate Action Tracker INDC | All $CO_2$ emissions | 9 % | Energy + Cement + LUCF + other |

Table 3 illustrates that “Trends”, though being presented as a business-as-usual scenario, produces global emission growth in line with the three INDC studies**.**

But what about regional emissions? Table 4 compares the two INDC interpretations for China and USA, where INDC projections are available. Other than the fact that regions below exactly replicate each other’s geography, the two regions in question also cover almost half of global GHG emissions in 2015: emissions from USA and China contribute to 15% and respectively 30% of global $CO_2$ emissions.

**Table 4: GHG emissions growth 2015–2030**

| | World | USA | China |
|---|---:|---:|---:|
| “Trends” | 5 % | −32 % | −3 % |
| IEA New Policies Scenario | 9 % | −11 % | 11 % |
| Climate Interactive INDC | 0 % | −28 % | 22 % |

In Table 4, one can note that while “Trends” allows for substantial increases in GHG emissions outside the emissions-declining USA and China, IEA and Climate Interactive forecasts strong emissions growth in China, which implies that very little emissions growth can take place elsewhere. The conclusion is that although the emission pathway of “Trends” is very close to the emission pathway of INDCs at the global level, they agree less at the regional level.

In Table 5, we further compare regional differences in fossil energy. Climate Interactive did not provide such data (but as seen in Table 4, Climate Interactive and IEA INDC analyses are comparable.) IEA *does* provide energy source breakdown.

**Table 5: Growth in energy use 2015–2030**

| | | Total Energy | Oil | Gas | Coal |
|---|---|---:|---:|---:|---:|
| World | “Trends” | 14 % | −4 % | 15 % | 1 % |
| | IEA NPS | 18 % | 8 % | −10 % | 7 % |
| USA | “Trends” | −20 % | −65 % | 14 % | −46 % |
| | IEA NPS | −2 % | −11 % | 7 % | −36 % |
| China | “Trends” | 22 % | −1 % | 159 % | −12 % |
| | IEA NPS | 22 % | 26 % | 126 % | 0 % |

In line with Table 4, “Trends” not only expects reduction in US’ energy consumption by 20%, but also foresees a cut in coal consumption by half and oil consumption by almost 2/3—and gas consumption to increase by 14%. The IEA New Policies Scenario (NPS) sees the total world consuming ever more oil and coal, while consuming far less gas. But in NPS these trends do not hold for the US, where coal and oil use is curbed significantly and, like in China, gas use is increased.

## What will it take to limit the global warming to 2°C?

Contrary to benchmark business-as-usual calculations of IEA and IPCC, our study indicates that INDC pledges reflects business-as-usual for the world as a whole, but with regional differences: Especially China will likely overachieve its INDC pledges, in line with Stern et al (2016). By the same token, USA will meet its pledges following well-established investment inertias in fossil and non-fossil fuels. This means that the rest of the world cannot follow business as usual, but must work hard to fulfill its pledges.

As is clear from the Paris Agreement (2015), however, INDC pledges will not be sufficient in limiting global warming to sustainable levels. We (among others, see e.g. IEA, 2015 and IPCC, 2015) have also investigated a plausible scenario limiting global warming to 2°C. We have compared the "Trends" energy system (that produces a 3°C world when applied throughout 2100) to one that one in line with a 2°C world. The measures will have to be extremely draconian. Compared to business as usual as established above, we have (Bakken & Özgün, 2016)

- Starting in 2015, reduced all fossil capacity additions linearly to 0 by 2030, and replacing the needed energy with non-fossil sources, in proportion to what "Trends" used,
- Significantly decoupled energy use from economic growth by increasing regions' annual energy efficiency improvements by 75% from what they were in "Trends" (thus reducing GDP's global energy intensity to 1/3 of today's levels, compared to "Trends" reduction to ½),
- Beginning in 2030, linearly increased use of carbon capture and storage so that it covers 50% of all gas and coal usage in 2050,

## Conclusion

Commonly, COP21 is seen as a major change in nations' commitment to solving the galloping global $CO_2$ emissions that will lead to serious climate change. We instead find that INDCs can be explained as extensions of policies already in place. As China "automatically" will overachieve on its pledges, and USA will deliver on them, it is only the rest of the world that will have to struggle and improve on its current policies. In a sense, nations and businesses have—seen as a whole—built up momentum that will lead them to fulfill the sum of pledges.

Meeting INDCs will not come automatically, but only require that existing level of decarbonization decision making continue. Hence, there is additional room for nations to up the stakes and provide more draconian measures. This is really needed, as the INDCs do not deliver a sustainable planet, but are consistent with a steadily warmer and climatically highly problematic future. Meeting INDCs will lead to stabilization around

3°C, far from sufficient for reaching the COP21 objectives of limiting global warning to 2°C.

Focusing on the energy system, which is the main cause of global warming, the present study points to that strategies that will lead us to a 2°C are also feasible. This will mean increasing by ¾ the rate of energy efficiency improvements, and a similar increase in the rate of uptake of renewable sources. This will also imply that no investments can be done to develop and extract from new fossil fields after 2030. That will be a challenge, in contrast to meeting the INDCs, and require fundamental transformation of the regional energy and other systems that emit GHG. We have no time to lose.

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**Appendix 1**

Below we summarize the details of the processes described in the main text. Variable names are in boldface.

**1.** We used BP energy consumption data (BP, 2015) (1965 to 2014) as **Historic Energy Consumption** (Figure 2). We assumed 2015 consumptions to be equal to those of 2014.

**2.** To calculate regional totals, we assumed Russia's and Ukraine's 1985 energy consumption shares in Soviet Union's are constant from 1965 to 1985.

**3.** We estimated **Capital Decay** assuming that **Historic Energy Consumption** to be removed at any year is equal to its **Historic Energy Consumption** divided by its **Capital Lifetime** (first-order delay), assuming following lifetimes: coal—50 yr, oil—50 yr, gas—50 yr, nuclear—50 yr, hydro—70 yr, solar—50 yr, wind—50 yr, other renewables—40 yr

**4.** We estimated **Synthetic Capacity Additions** by taking the difference between two consecutive years' **Historic Energy Consumptions** and adding **Estimated Capital Decay** for that year, allowing negative **Synthetic Capacity Additions**.

**5.** For years 1970 to 2010, we calculated **Smoothed Synthetic Capacity Additions** (Figure 4) by taking mean values of **Synthetic Capacity Additions** from 4 years earlier to 4 years ahead of any year (covering 9 years)

**6.** For non-renewables from 2011 to 2014, we calculated **Smoothed Synthetic Capacity Additions** by taking mean values of **Synthetic Capacity Additions** over shorter intervals, covering symmetrical number of years from current year to 2014 and from current year back to same number of years.

**7.** For renewables, we calculated **Smoothed Synthetic Capacity Additions** of 2011 by taking mean values of **Synthetic Capacity Additions** from 3 years earlier to 4 years ahead.

**8.** For renewables from 2012 to 2014, we calculated **Smoothed Synthetic Capacity Additions** by multiplying **Estimated Total Renewable Additions** with **Estimated Share of Renewables in Additions**. **Estimated Total Renewable Additions** for each region is calculated from linear trend extrapolation model between the sums of 2005–2011 renewable **Smoothed Additions** and **Total Investments in Renewables**. **Total Investment in Renewables** shows total monetary investments made in renewables and is taken from UNEP Bloomberg New Energy Finance report (McCrone et al 2015). For USA and China, the data was available. For OECD, the data is estimated by subtracting USA's investments from Developed countries' investment. BRISE data was estimated by adding investments of Brazil and India (for both, data is available for all years) and South Africa, Mexico, Turkey, Chile, Thailand, Vietnam, Iran, Argentina and Venezuela (for which data availability varied from year to year). Rest of the world (ROW) data was estimated by subtracting USA, China, OECD and BRISE estimates from the World total. **Estimated Share of Renewables in Additions** represent the shares of Hydro, Solar, Wind and Other Renewables in total investment in renewables, and are estimated by extrapolating the global trends of capacity per unit investment ratios of 2004–2011 period (with different periods and curve types used for different energy sources) to 2012–2014, and multiplying this with regional investment estimates (which is calculated by applying 2012–2014 global growth trends of renewable energy sources to 2011 estimates of regional energy investments).

**9. Trend Based Capacity Additions** use one of three time-series model to forecast capacity additions for years 2015 to 2050 based on **Smoothed Synthetic Capacity Additions** series from 2004 to 2014. These time-series model types use one of two data sources: **Synthetic Capacity Additions** or **Changes to Synthetic Capacity Additions**: for both, linear extrapolations were attempted. For **Synthetic Capacity Additions**, quadratic polynomial was also attempted. The rule was to use linear extrapolations to **Synthetic Capacity Additions**, with the following exceptions: quadratic polynomial extrapolations based on **Synthetic Capacity Additions** for USA Gas (since linear extrapolation showed unrealistic growth—tripling from 2015—quadratic polynomial was more realistic as it was the faster declining option), China Solar (since the other two alternatives were unable to reflect the expected accelerating growth), ROW Coal (since the other two alternatives showed decline, while rising energy demand in ROW dictates capacity additions); linear extrapolations based on **Changes to Synthetic Capacity Additions** for China Oil (since linear extrapolation showed unrealistic growth and the selected option dictated the least capacity additions—in line with expectations), OECD Gas (since other two models indicated immediate decline to zero at year 2015), USA Other Renewables, China Other Renewables, OECD Other Renewables, BRISE Other Renewables (since this option showed boom-and-bust behavior for all four ‘Other Renewables’ series—the most reasonable behavior mode expected for this energy source). As further exceptions, the following do not follow one of three time-series models: USA Solar, China Hydro, OECD Solar, BRISE Solar, ROW Solar, ROW Wind, ROW Other Renewables. USA Solar, OECD Solar, BRISE Solar and ROW Solar are assumed to be identical to China Solar. China Hydro's model parameters are modified to account for the hydropower resource availability in China. Similarly, the parameters of ROW Wind and ROW Other Renewables are manually set, as none of the models yielded reasonable results.

In Table A1, we present trend types and parameters we used for each region and energy source to forecast capacity additions. The equations are of the following forms.

Linear: $p_1 + p_2 \times t$

Quadratic: $p_1 + p_2 \times t + p_3 \times t^2$

Exponential: Cap.Add.(2015) × $(1 + p_1 + p_2 \times t)$

where $t$ is time in calendar years.

**10.** Total **Energy Demand** (Figure 5) is externally determined for five regions. (See the text for an explanation of how it is derived from assumptions presented in Appendix 2).

**11. Forced Retirements** are based on the difference between total **Energy Demand** and total **Energy Supply** for the previous year. We assumed that only Oil, Coal and Gas capacities may be forcefully retired, with that order or priority. We further assumed that share of capacity that may be retired is capped at 0% for 2015, 2.5% for 2016, 5% for 2017 and 7.5% for 2018 and the following years.

**Table A1. Trend types and parameters (Alvik et al, 2015)**

| Region | | Energy Source | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Coal | Oil | Gas | Nuclear | Hydro | Solar | Wind | Other Renewables |
| USA | Type | Linear | Linear | Quadratic | Linear | Linear | Quadratic | Linear | Exponential |
| | $p_1$ | 1069.497 | 28.95095 | −579470 | 287.2145 | 372.3615 | 60521.09 | −657.134 | 55.87776 |
| | $p_2$ | −0.53158 | −0.00945 | 574.8041 | −0.141 | −0.18497 | −60.4758 | 0.329124 | −0.02776 |
| | $p_3$ | | | −0.14254 | | | 0.015108 | | |
| China | Type | Linear | Exponential | Linear | Linear | Exponential | Quadratic | Linear | Exponential |
| | $p_1$ | 11702.4 | 13.72221 | −2227.31 | −342.85 | 10.38608 | 60521.09 | −1750.08 | 106.9561 |
| | $p_2$ | −5.76801 | −0.00682 | 1.115932 | 0.171759 | −0.00513 | −60.4758 | 0.873374 | −0.05304 |
| | $p_3$ | | | | | | 0.015108 | | |
| OECD | Type | Linear | Linear | Exponential | Linear | Linear | Quadratic | Linear | Exponential |
| | $p_1$ | 361.4341 | 2768.838 | 27.97254 | 1098.621 | −134.418 | 60521.09 | −668.178 | 32.37536 |
| | $p_2$ | −0.17506 | −1.37393 | −0.01398 | −0.54621 | 0.069097 | −60.4758 | 0.335341 | −0.01608 |
| | $p_3$ | | | | | | 0.015108 | | |
| BRISE | Type | Linear | Linear | Linear | Linear | Linear | Quadratic | Linear | Exponential |
| | $p_1$ | −2759.81 | −1738.89 | 2470.818 | −158.136 | 1140.571 | 60521.09 | −522.496 | 23.91629 |
| | $p_2$ | 1.391814 | 0.887612 | −1.20972 | 0.080168 | −0.56447 | −60.4758 | 0.260941 | −0.01185 |
| | $p_3$ | | | | | | 0.015108 | | |
| ROW | Type | Quadratic | Linear | Linear | Linear | Linear | Quadratic | Linear | Exponential |
| | $p_1$ | 108605.5 | −826.3 | 149.7825 | 18.99218 | 159.8248 | 60521.09 | −1760.08 | 10 |
| | $p_2$ | −107.942 | 0.424367 | −0.06098 | −0.00931 | −0.0776 | −60.4758 | 0.873374 | −0.0049 |
| | $p_3$ | 0.026822 | | | | | 0.015108 | | |

## Appendix 2

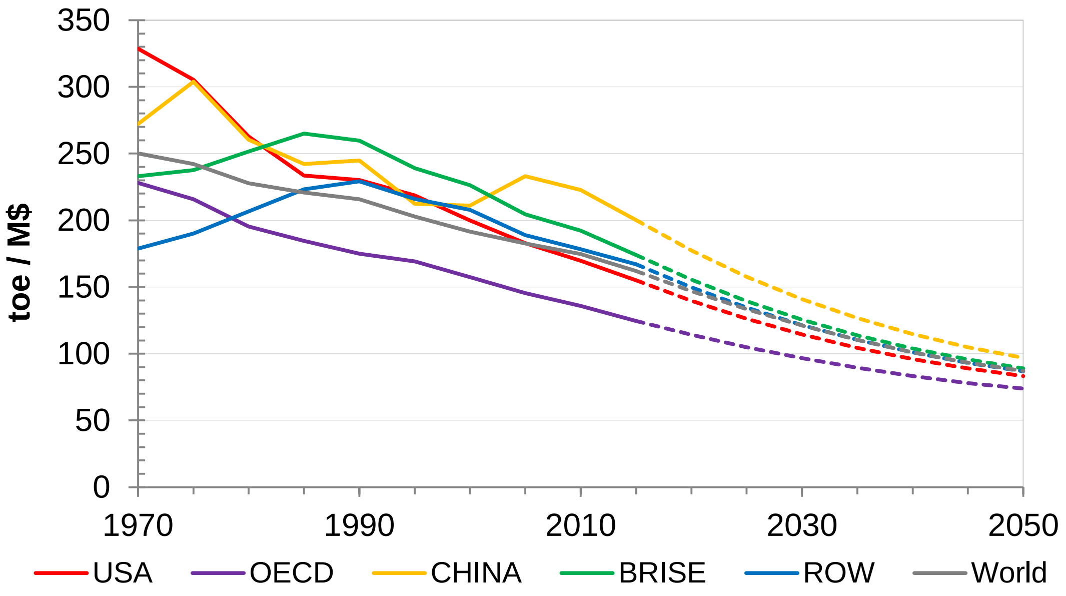


**Figure A1. Energy intensity forecasts for the “Trends” scenario.**

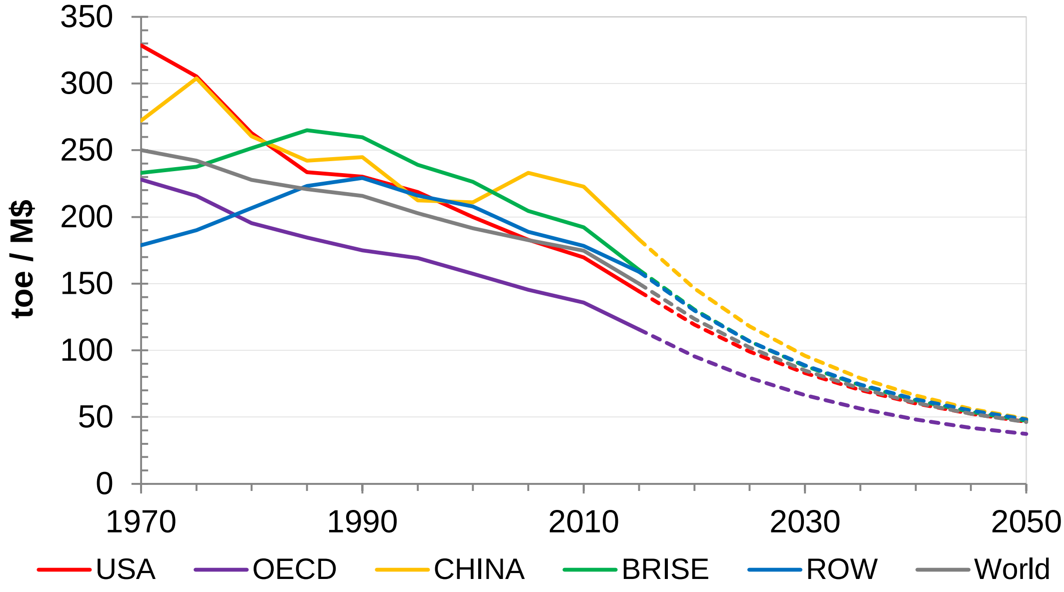


**Figure A2. Energy intensity forecasts for the "2°C" scenario.**

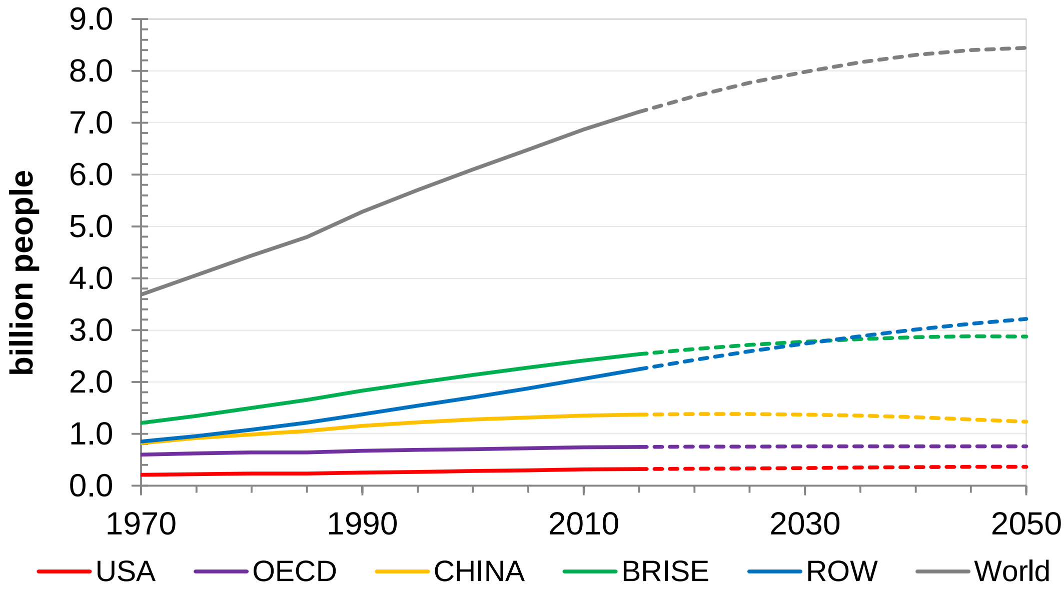


**Figure A3. Population forecasts used in both "Trends" and "2°C" scenarios.**

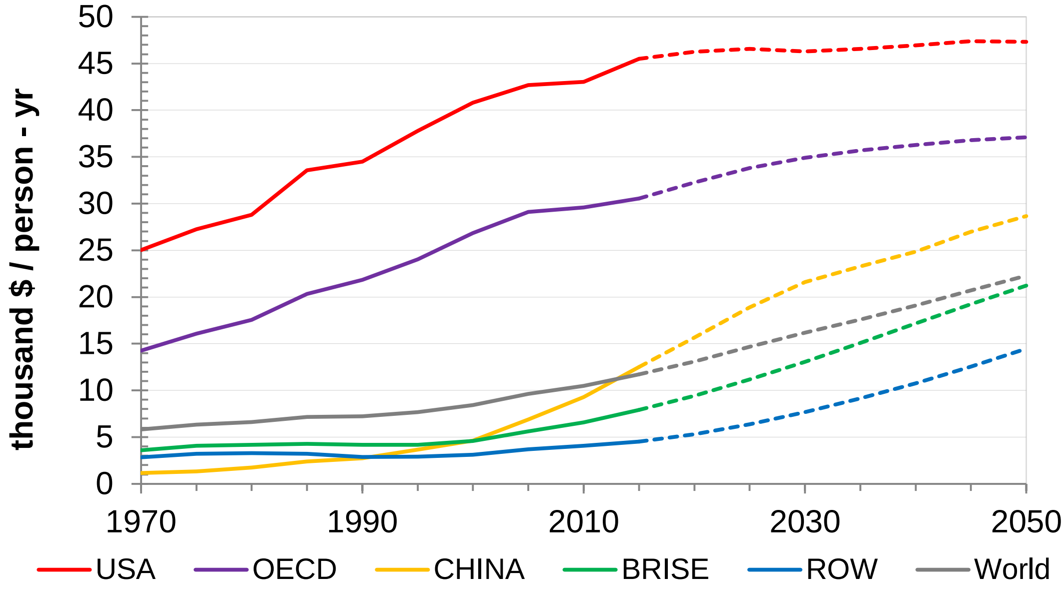


**Figure A4. Productivity forecasts used in both "Trends" and "2°C" scenarios.**

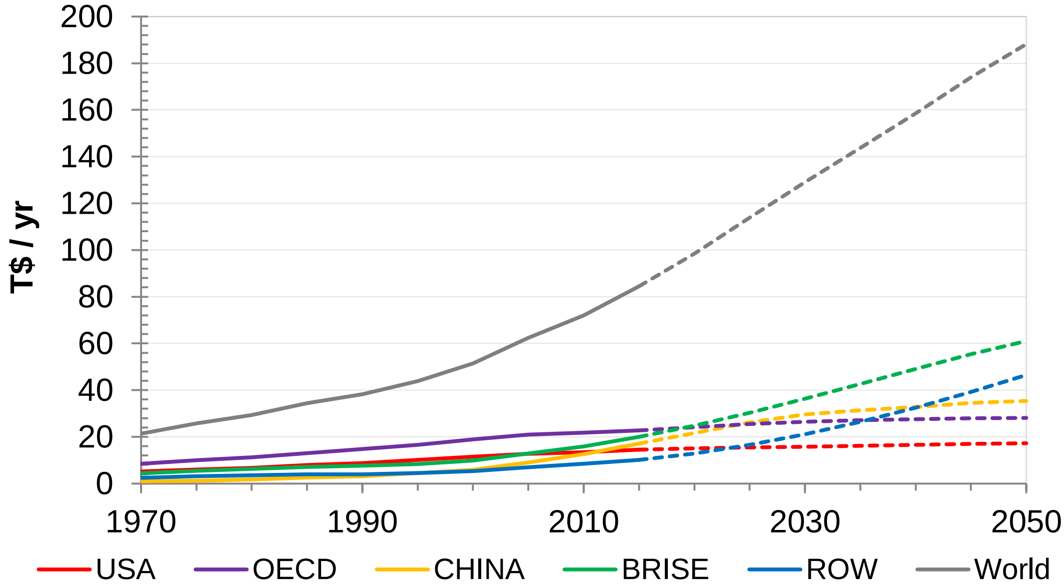


**Figure A5. GDP projections for both "Trends" and "2°C" scenarios.**