Short term policies to keep the door open for Paris climate goals

Supplementary Online Material

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Contents

S1. Supplementary Figures and Tables .............................................................................................................. 2
  S1.1. Scenario characteristics ........................................................................................................................ 2
  S1.2. Decomposition of strengthened policy packages into CO2 pricing and sectoral measures .................. 3
  S1.3. Implementability indicators .................................................................................................................. 5
    S1.3.1 Time profiles of global implementability indicators in alphabetical order ....................................... 5
    S1.3.2 Additional implementability indicators not shown in main paper ................................................. 12

S2. Supplementary Information on scenario definition and implementation .................................................... 14
  S2.1 Detailed description of the good practice and net-zero benchmarks .................................................. 14
  S2.2 Policy impact calculations for the buildings sector ............................................................................ 17
    S2.2.1 Space heating and cooling ............................................................................................................ 17
    S2.2.2 Appliances and lighting ................................................................................................................ 19
  S2.3 Policy impact calculations for the transport sector ............................................................................ 20
    S2.3.1 Passenger transport ..................................................................................................................... 20
    S2.3.2 Freight transport .......................................................................................................................... 20

S3. Supplementary Information on the modeling framework ........................................................................... 21

References...................................................................................................................................................... 22
**S1. Supplementary Figures and Tables**

**S1.1. Scenario characteristics**

![Figure S1: Kyoto GHG emissions trajectories](image)

*Figure S1*: Kyoto GHG emissions trajectories towards the well below 2°C target with full (left) and limited CDR availability (center) and towards the 1.5°C target with full CDR availability (right panel) plus the cost-effective pricing pathway that reaches 1.5°C by the end of the century with limited CDR availability.

| CO₂ prices ($/t CO₂) | NDCs until 2030 | Good Practice | Net Zero | Cost-effective carbon pricing |
|----------------------|-----------------|---------------|----------|------------------------------|
| 2°C full CDR         | 194             | 175           | 162      | 155                          |
| 2°C red. CDR         | 636             | 501           | 423      | 278                          |
| 1.5°C full CDR       | 412             | 376           | 327      | 272                          |
| 1.5°C red. CDR       | -               | -             | -        | 1056                         |

*Table S1*: Global CO₂ prices in 2050 (in $/t CO₂) across the mitigation scenario set. For the case of limited CDR availability, the budget target associated with the 1.5°C scenario was only feasible to reach under cost-effective pricing after 2020.
S1.2. Decomposition of strengthened policy packages into CO₂ pricing and sectoral measures

Additional to the scenarios presented in the main paper, Figure S3 presents four further scenarios that help understand to what extent the strengthened CO₂ pricing and the strengthened sectoral measures each contribute to the additional mitigation beyond NDCs. For this purpose, both for the Good Practice and the Net Zero scenario, we calculate a scenario in which only one of these components is strengthened while the other is being kept constant at the NDC scenario level. Both components achieve similar levels of additional abatement, with the technology policy options slightly outperforming the pricing policy. As CO₂ prices and sectoral policies partly incentivize the same technology shifts, each of these options alone already achieves more than half of the total abatement in each respective strengthened policy package.

As our study focuses on the effect of the aggregate policy package on achievability of long-term climate targets, as assessed by the diverse set of implementability indicators, we do not analyze the individual effect of single technology measures. A comparative evaluation of the relative strength of these measures can be found in Fekete et al. (2015), especially Figure 2 therein, while Bertram et al. (2015) offers an analysis of the interaction of two important types of technology measures in the power sector, namely a coal moratorium and a push of renewable power technologies.

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Figure S2: Regional CO₂ prices until 2050 for the four policy scenarios towards well below 2°C with full CDR availability. Globally converged carbon prices in 2050 are listed in Table S1 for the full scenario set.
Figure S3: a) Emission trajectories for 2°C scenarios with full CDR availability from main paper, plus four additional scenarios with either only strengthened CO2 price (“-price”), or only strengthened sectoral technology policies (“-tech”). b) Additional abatement in 2030 with respect to the NDC scenario. The percentage values above the additional scenarios show how much of abatement of the combined strengthened scenario is achieved by the individual component alone. Please note that the values add up to more than 100%, as CO2 prices and sectoral policies partly incentivize the same technology shifts.
S1.3. Implementability indicators

This section presents the details of the calculations for the implementability indicators presented in Table 3 and Figure 3 of the main paper. Next to the equations, time series for the indicators illustrate how the maximum value (depicted by the dots) used in the main paper is representative for the challenge and in which time step it occurs. The long variable names in single quotation marks (for example ‘Price|Carbon’) refer to variable names according to the IAMC reporting template, used e.g. in the AR5 database, where a definition file including most of these can also be downloaded: https://tntcat.iiasa.ac.at/AR5DB/static/download/AR5DB_data_template_final.xlsx.

S.1.3.1 Time profiles of global implementability indicators in alphabetical order

ConsLossCum

This indicator describes net present value consumption losses in the mitigation scenario relative to the baseline consumption, discounted at 5%/yr.

- BaseCons = ‘Consumption’NoPolicy scenario
- ‘Policy Cost | Consumption Loss’ = BaseCons−‘Consumption’Policy scenario
- ConsLoss = ‘Policy Cost | Consumption Loss’ / BaseCons x 100%
- ConsLossCum = Σ_{t=2015→T}[‘Policy Cost | Consumption Loss’ x(1.05)^{(t-2015)}] / Σ_{t=2015→T}BaseCons x 100%

Figure S4: Time series for the implementability indicator ConsLossCum (bottom row) and the underlying development of percentage consumption losses relative to baseline consumption over time (top row).
CO2EmiRed & CO2EmiBreak

These indicators describe the annual average decadal reduction rate of gross CO₂ emissions from fossil fuel combustion and industrial processes (CO2EmiRed) and the resulting change in reduction rate between two decades (CO2EmiBreak).

- Emi FFI = ‘Emissions|CO2|Fossil Fuels and Industry’  
  + ‘Emissions|CO2|Carbon Capture and Storage|Biomass’

- CO2EmiRed = [Emi FFI(t−5 a)−Emi FFI(t+5 a)]/Emi FFI(t−5 a) ×100%/10 a

- CO2EmiBreak = CO2EmiRed(t + 5a) − CO2EmiRed(t − 5a)

Figure S5: Time-series for the implementability indicators CO2EmiBreak (top row) and CO2EmiRed (center row) as well as the underlying gross CO₂ emissions from fossil fuel combustion and industrial processes (bottom row).
**CO2PriceInc**

This indicator captures the annual average CO2 price increase over a decade. For this analysis, we use the maximum between 2020-2040.

- \( CO2PriceInc = \frac{\text{Price}_t + 5 - \text{Price}_t - 5}{10} \)

**CoalIdleCap**

This indicator captures the early retirement of power plants. It is defined as the total capacity of plants that the model has decided to retire prematurely (i.e. before the end of its fixed technical lifetime).

- \( CoalIdleCap = \text{Idle Cap}_t \)

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**Figure S6:** Time-series for the implementability indicator CO2PriceInc (bottom row), as well as the underlying CO2 price trajectory (top row).

**Figure S7:** Time series for the implementability indicator CoalIdleCap.
CumNegEmi

This variable captures the cumulative amount of net negative CO₂ emission until 2100.

- $\text{Emi} = \text{Emissions} \mid \text{CO}_2$
- $\text{CumNegEmi} = \sum_{t=2005}^{2100} \min(0, \text{Emi}(t))$

*Figure S8: Time series for the implementability indicators CumNegEmi (top row) and the underlying trajectory of net CO₂ emissions (including fossil fuel combustion, industrial processes, land use and anthropogenic carbon dioxide removal) (bottom row).*
**FoodPriceInc**

As an indicator of decadal growth in food commodity prices, we analyse a chained Laspeyres price index that weights prices based on food baskets in the previous period. Food baskets are defined on exogenous regional demand. The 2005 index level is set to 1.

\[
\text{FPX} = \text{‘Price|Agriculture|Non-Energy Crops and Livestock|Index’}
\]

- **FoodPriceInc** = \( \frac{\text{FPX} (t+5 \ a) - \text{FPX} (t-5 \ a)}{10 \ a} \times 100\% \)

*Figure S9: Time series for the implementability indicator FoodPriceInc (bottom row) and the underlying development of the food commodity price index (top row).*
**MaxCCS, CCSDepInc**

These indicators capture the annual CCS deployment, and the decadal increase of CCS deployment. The cumulative amount of CCS over the 21st century is also shown.

- CCS = ‘Emissions | CO2 | Carbon Capture and Storage’
- CCSDepInc = CCS(t + 5 a) − CCS(t−5 a)

*Figure S10: Time series for the implementability indicators MaxCCS (bottom row) and CCSDepInc (top row) and cumulative CCS deployment over the 21st century (middle row).*
LandBioAff & LandBioAffInc

This indicators capture the combined area for afforestation and bioenergy crops and its annual average increase over a decade. The land area in 2100 and the maximum increase were used as part of the set of implementability indicators in the main paper.

- LandBioAff = ‘Land Cover|Cropland|Energy Crops’ + ‘Land Cover|Forest|Managed|Afforestation’
- LandBioAffInc = (LandBioAff (t+5 a)−LandBioAff (t−5 a))/10 a

Figure S11: Time series for the implementability indicators LandBioAff (third row) and LandBioAffInc (bottom row). The underlying time series for afforestation area (top row) and bioenergy cropland area (second row) are also shown.
S.1.3.2 Additional implementability indicators not shown in main paper

The list of implementability challenges in Table 2 and Figure 3 of the main paper could obviously be expanded further. To keep the number of indicators limited, we have focused on indicators that are linked to crucial debates and additionally exhibit a strong variation across the analyzed scenario set. The selection of technologies represented by these indicators however by now means implies that other technologies such as wind or nuclear power could not also face substantial societal hurdles. The absolute deployment of these technologies however does not vary strongly across the analyzed scenario set (cumulative deployment from 2005-2100 is between 5797 EJ -6997 EJ for wind, and 1588 – 1794 EJ for nuclear).

Figures S12 and S13 show indicators for the annual average decadal increase of non-biomass renewable power generation (wind, solar, geothermal and hydro) and the annual average decadal increase of investments into these technologies. The indicator on annual deployment increases of renewable power technologies shows a similar pattern compared to other “speed” indicators (CO₂ emissions reductions and afforestation and bioenergy land area increase) and the indicator on increases in annual investments in renewable power technologies shows a similar pattern as the “disruptiveness indicators” (CO₂ emissions trend break and idle coal power capacity). They were therefore not added to the main paper.

RenDep & RenDepInc

- **RenDep** = ‘Secondary Energy | Electricity | Non-Biomass Renewables’
- **RenDepInc** = \[\frac{\text{RenDep}(t+5 \text{ a}) - \text{RenDep}(t-5 \text{ a})}{10 \text{ a}}\]

*Figure S12: Time series for the implementability indicators RenDep (top row) and RenDepInc (bottom row)*
RenInv & RenInvInc

- RenInv = ‘Investments|Energy|Electricity|Non-Biomass Renewables’
- RenInvInc = (RenInv (t+5 a) − RenInv (t−5 a))/10 a

Figure S13: Time series for the implementability indicators RenInv (top row) and RenInvInc (bottom row)
S2. Supplementary Information on scenario definition and implementation

S2.1 Detailed description of the good practice and net-zero benchmarks

For renewable electricity, the share in global total electricity generation has increased from 18% in 2005 to 22% in 2014 (including hydro) with an average annual increase of 0.49 %-point/year during 2005–2014 (IEA, 2016c). For good practice policy package, we refer to the EU-28, where the share during the same period increased on average 1.5%-point/year including hydro and 1.3%-point/year excluding hydro. The main EU-level policy is the Renewable Energy Directive (European Parliament, 2009). To take into account higher hurdles for the ramp-up of capital-intensive renewables in developing countries (Hirth and Steckel, 2016), we slightly differentiated the target growth rate from 1.25%/yr (MEA, AFR, see table S3 for region definitions), 1.35%/yr (CHN,ROW,IND,RUS,LAM,OAS) to 1.45%/yr (EUR,JPN,USA) per region, based on empiric estimates on the weighted average cost of capital (Ondraczek, Komendantova and Patt, 2015). For the time-step 2020 in REMIND, only a slightly higher value than in the NDC scenarios was prescribed, and the linear yearly growth bound was applied for subsequent periods, limited at maximum shares of 50% to 80%.

For the phase out of unabated coal-fired power plants (i.e. without CCS), a number of countries in the EU are planning to phase out coal-fired power plants (Jones and Gutmann, 2015). At sub-national level, Alberta (Government of Alberta, no date), and Ontario in Canada phased them out in 2014 (Harris, Beck and Gerasimchuk, 2015), and South Australia in 2016 (Parkinson, 2016). Canada has a plan to phase out coal power plants without CCS by 2030 (Government of Canada, 2016). India’s Draft Electricity Plan (Central Electricity Authority, 2016) also projected that no new coal-fired power plants would be needed between 2022 and 2027. The net zero policy benchmark agrees with the decarbonisation pathways required to keep warming below 1.5 °C and therefore includes a ban of new gas-fired power plants without CCS (Kuramochi et al., 2017). Developed countries are assumed to achieve the policy benchmarks 5 to 10 years earlier than in developing countries. This policy was implemented by fixing new investments into the respective technologies at zero in the respective regions and periods. The data on new coal power plant construction presented in Table 1 in the article is taken from (Shearer, Fofrich and Davis, 2017).

For the industrial energy efficiency, we found insufficient evidence that existing policies in major emitting countries have made significant impact well beyond business-as-usual. Our good practice benchmark therefore is based on the findings of techno-economic potential assessment studies (UNIDO, 2010; Banerjee et al., 2012). The literature suggests that the autonomous EE improvement is about 1%/yr (Blok, 2004; UNIDO, 2010) and the improvement of anywhere close to 2%/yr is considered to be challenging, especially in developed economies (Blok, 2004). For this policy, the efficiency targets have been translated into total final energy savings with respect to the current policy trajectory, and this values have been used to calculate a maximum bound on industrial final energy in REMIND.

For industrial CCS, no countries have targets or mandatory requirements (Global CCS Institute, 2016). As of June 2017, the total capacity in operation and under construction is 34.6 MtCO₂/yr (Global CCS Institute, 2017). We distinguished two types of industrial CCS by the difference of motives: enhanced oil recovery (EOR) and dedicated geological storage. To develop the good practice benchmark, for EOR-CCS we applied the the highest CO₂ removal capacity installed per unit of crude
oil production observed at the country level (i.e. the United States) in 2014 to the global total crude oil production in 2014, and for dedicated CCS we applied the average CCS installation rate per industrial CO₂ emission for the countries with large scale CCS plants to the global total industrial CO₂ emissions in 2014 (Enerdata, 2016; IEA, 2016b). For the net zero policy benchmark, the world average installation rate for dedicated CCS in 2030 reaches the highest observed among the countries with large-scale plants today (i.e. Australia). These targets are implemented as minimum bounds on industrial CCS use in REMIND.

For good practice in heating and cooling for new buildings, we refer to the EU Energy Performance of Buildings Directive (EU Parliament, 2010), which aims for all new buildings to be nearly zero energy by 2020. There is no common definition of “near zero” energy buildings within the EU. We therefore set energy consumption levels at 22 kWh/m²/yr for residential buildings and 30 kWh/m²/yr for commercial buildings based on the definitions observed across EU member states (BPIE, 2016). The current retrofit rate for existing buildings is around 1%/yr (BPIE, 2014; Ürge-Vorsatz et al., 2015). In the good practice scenario, the retrofit rate increases to between 1.5% and 2.1%/yr based on region (Ibid.). Good practice efficiency improvements through renovation are based on a German government program that provides financial support for renovations that improve energy efficiency by 45% relative to a similar reference building (KfW, 2017).

For electrical appliances and lighting, we refer to Japan’s Top Runner Program (METI, 2015). The EE improvement rates for 24 appliances (including heating and cooling as well as cooking) over varying time periods of 4 to 9 years was on average 0.9%-point/yr higher than the targeted rates (Ibid.). Assuming the target level is no worse than a business-as-usual and an average lifetime of 10 years, this corresponds to roughly 0.5%/yr improvement additional to business-as-usual improvement on a stock average. The impact of this set of measures on buildings final energy consumption has been assessed with a spreadsheet model (see section S2.2), and the resulting values for relative final energy reduction below the current policy scenario have been applied in REMIND to set maximum bounds on total buildings final energy.

The global market share for electric vehicles (EVs) was a mere 0.8% in 2016 (EV-Volumes, 2017). In Norway, however EVs (including plug-in hybrids) account for nearly 30% of new car sales in 2016 (IEA, 2017). This value therefore has been used as 2030 target for middle- and high-income countries (EUR, JPN, CHN, OAS, ROW, USA, see table S3 for region definitions) in the good practice scenario, while 20% is the target in low-income countries (AFR, LAM, RUS, MEA, IND). A multi-layered policy package comprised of financial incentives and behavioural incentives (e.g. allowing EV drivers onto bus lanes and free public parking) contributed to high EV sales (Figenbaum, Assum and Kolbenstvedt, 2015). The net zero benchmark value is roughly in line with the phase-out plans of petrol and diesel passenger vehicles in the UK and France (DEFRA and DfT, 2017; Ewing, 2017) and slower than Norway’s plan by 2025 (Avinor et al., 2016). The share target in 2030 was directly implemented in REMIND. Due to the representation of limits on the diffusion speed in REMIND, the target in 2030 leads to higher deployment of EV technology already before 2030.

For fuel economy of new vehicles, the EU sets one of the strictest standards in the world (Yang and Bandivadekar, 2017). We extrapolated the EU proposal on the CO₂ emission standards for 2025 to 2030. The good practice value also fits the extrapolation of the trend observed for new vehicles in Japan between 2000 and 2013 (ICCT, 2015). We also took into account the performance gap between test mode and real-world fuel-economy figures, estimated at 30% (ICCT, 2016).
For freight transport, only Japan, the U.S., Canada and China have CO₂ or efficiency standards for heavy duty vehicles (Muncrief and Rodriguez, 2017); the U.S. and Canada have separate engine standards in addition to full-vehicle regulations including aerodynamic and rolling resistance to specifically drive improvements in engine efficiency. For the good practice benchmark we refer to the U.S. fuel efficiency standards (U.S. Environmental Protection Agency and U.S. Department of Transportation, 2016). We applied the rate of strengthening in fuel efficiency standards between 2017 and 2030 because this sub-sector is highly heterogeneous in terms of truck size and average load that the values from the U.S. standards cannot be applied directly.

For international shipping and aviation, the International Civil Aviation Organization (ICAO) adopted the targets of improving average fuel efficiency by 2% yr, carbon neutral growth from 2020 onwards and reducing its carbon emissions by 50% by 2050 compared to 2005 levels (ICAO, 2010). The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) supports those targets (ICAO, 2017). The International Maritime Organization (IMO) is also preparing a strategy for GHG reductions (IMO, 2017). Historical data on international bunkers’ CO₂ emissions growth (2005-2014) is based on IEA (IEA, 2016b). Net zero benchmarks were based on IEA (IEA, 2016d). The impact of the set of measures on transport final energy consumption has been assessed with a spreadsheet model (see section S2.3), and the resulting values for relative final energy reduction below the current policy scenario have been applied in REMIND to set maximum bounds on total transport final energy, in parallel to the EV share target described above.

For agricultural emissions, anaerobic digesters have been widely used in countries such as China, Germany, India and the US due to policy support (Sam, Bi and Farnsworth, 2017) and there is large potential globally for their further deployment. Gerber et al. (2013) assumes in its mitigation scenario that the manure coverage rate by anaerobic digestion can potentially be increased to 60%, compared to 7% in 2005 in East and Southeast Asia and to 40% for Germany and the USA (no reference historical data provided). This study uses 30% coverage of manure by 2030, from the current 10% (as per SSP2) as a good practice benchmark. In addition to anaerobic digesters, besides we also considered a marginal reduction in CH₄ intensity per tonne of rice production by 2030.

Finally, the nitrogen related emission from fertilizer application on cropland are treted through the rate of nitrogen use efficiency (NUE). We consider some aspects of NUE which include: attainable NUE (Godinot et al., 2016), desirable range of NUE (Nitrogen Use Efficiency (NUE) an indicator for the utilization of nitrogen in food systems, 2015), and other generally agreed ranges of NUE estimates (Smil, 1999; Lassaletta et al., 2016). For a good practice scenario, we use 10% point increase of NUE in 2030 compared to current global 52% of NUE. The estimates are further regionally varied. For the LULUCF sector, we refer to the New York Declaration on Forests (New York Declaration on Forests, 2014). Both good practice and net zero policy benchmarks are in line with the zero natural forest loss target (including other biomes with high vegetation carbon stocks) and the afforestation target (10 million ha forest land annually by 2030). The historical net forest loss data for 2000-2010 is based on FAO (FAO, 2016).

For carbon pricing, in both the good practice and net-zero scenarios the prices are set to the maximum of the region-specific carbon price resulting from emission (intensity) targets in the NDC scenarios, and a linearly increasing price trajectory starting at 5$/t CO₂ in 2020 and increasing by 1 (2)\$/ year in the good practice (net zero) scenario. As an exception, the yearly increase assumed for China is slightly higher at 1.5 (2.5)\$/ year in the good practice (net zero) scenario, as this
country has already announced to introduce a national emission trading system. The resulting carbon prices can be seen in Figure S2.

S2.2 Policy impact calculations for the buildings sector
For projecting energy use in the buildings sector, we divided the sector into three subsectors: space heating and cooling (SH&C), appliances and lighting, and others. The impact of strengthened policies on SH&C and appliances and lighting subsectors are first calculated using a tool based on the IEA Energy Technology Perspectives 2016 (IEA, 2016a). The detailed calculation steps are described below:

S2.2.1 Space heating and cooling
We developed three scenarios for energy use from SH&C in residential and commercial buildings. The current policy scenario is based on the IEA ETP’s 6DS scenario (IEA, 2016a). The good practice and net-zero scenarios have progressively strengthened policies for renovation rates, renovation efficiency improvements, and energy efficiency in new buildings.

Two key elements are needed to project SH&C energy use into the future: the floor area (m²) and energy intensity (kWh/m²/year) developments. At each annual time step, some floor area is renovated, some floor area is demolished, and some new floor area is built to replace the demolished buildings and account for new floor space.

For each type of building x (existing in 2010, renovated, and new) at each time step t (one year), total energy use is equal to (Eq. 1):

\[ \text{Total energy}_x(t) = \text{floor area}_x(t) \times \text{energy intensity}_x(t) + A(t) \]  

Eq. 1

The total energy use for all buildings at each time step is equal to the sum of total energy for each of the building types.

Total floor area projections (for residential as well as commercial buildings) are taken from (IEA, 2013), and were used in the 2013 edition of IEA’s ETP scenarios. The floor area projections used in the 2016 ETP are not publicly available. All floor area in the base year (2010) is considered to be old building stock, and this is the only building stock considered “old” in the model, i.e. stock built or renovated after 2010 is never demolished or renovated again, an assumption that is valid because the model results are only used until 2030. This old stock built before 2010 is then progressively renovated or demolished over time. The renovation rates and demolition rates for each scenario are summarized in Table S2. The renovation rates are differentiated by region in the good practice scenario. The demolition rates are differentiated for OECD and non-OECD countries in all scenarios. Renovation rates increase linearly from the base year rate to the target year rate over the implementation period.

The energy intensity (energy/floor area) is defined for each type of building at each time step. The intensity for old buildings in the base year is calculated based on (IEA, 2016a) and (IEA, 2013) and does not change over time. In the current policy scenario, the energy intensity for renovated buildings is 10% lower than that of old buildings (built before 2010). In the good practice scenario, the energy intensity for renovated buildings is 45% less than that of old buildings (built before 2010). In the net zero scenario, the energy intensity for renovated buildings is the same as new buildings,
except when this would lead to an increase in intensity (ASEAN and Brazil), in which case the intensity is the same as in the good practice scenario. New buildings have intensities of 22 kWh/m²/year for residential buildings and 30 kWh/m²/year for commercial buildings in the good practice and net zero scenarios, and the same intensity as old buildings in the current policies scenario. Intensities decrease linearly between the base year and the target year for each scenario over the implementation period.

$A(t)$ is a factor that represents the change in the average energy use intensity for all buildings that is not accounted for through building stock turnover (demolition, renovation, and new buildings). For example, installing more efficient air conditioning or heating units could lead to a factor $A(t)$ of less than 1 and represent a decrease in intensity. This effect is observed in the EU. However, additional use of air conditioning units because of increasing wealth would lead to a factor $A(t)$ of greater than 1 and represent an increase in intensity. This effect is seen in India. $A(t)$ was calibrated for each ETP country/region such that the current policy scenario matches the IEA ETP 6DS scenario, and was then applied to the good practice and net zero scenarios.

**Table S2: Summary of parameters for SH&C energy consumption in buildings in each scenario.**

| Scenario name      | Demolition rate | Renovation rate | Renovation efficiency improvement | Energy intensity for new buildings | Time period within which targets are achieved |
|--------------------|-----------------|-----------------|-----------------------------------|----------------------------------|---------------------------------------------|
| Current Policies   | 2.0%/yr (OECD)  | 1.4%/yr (all regions) | 10%                              | Equal to that of old buildings   | N/A                                         |
| Good Practice      | No change compared to current policies | 2.1%/yr (OECD) | 45%                              | 22 kWh/m²/year (residential) 30 kWh/m²/year (commercial) | 2018 – 2020 (OECD) 2018 – 2030 (non-OECD) |
| Net Zero           | Same as good practice | 3%/yr (all regions) | The value that would result in the same intensity as new buildings | Same as good practice | 2018 – 2020 (OECD) 2018 – 2025 (non-OECD) |

1) Demolition rates based on (IEA, 2016a).

2) Renovation rates for all scenarios based on (Global Buildings Performance Network, 2013) and (Ürge-Vorsatz et al., 2012), which both use the 3CSEP HEB model hosted at Central European University. Regional differentiation in the Good Practice scenario is intended to capture regional differences in realistically achievable renovation rates.

3) Renovation efficiency improvement compared to old buildings for current policies scenario based on (Global Buildings Performance Network, 2013). Regional differentiation is implicitly included by referencing to a base year level for that region.

4) Renovation efficiency improvement compared to old buildings for good practice scenario after German government subsidies for buildings renovations reaching this level (KfW, 2017).

5) Energy intensities for new buildings are based on common definitions of zero energy buildings in EU countries (definitions vary among countries) (BPIE, 2016). For some regions (Brazil, ASEAN), this intensity represents an increase in intensity from 2013 values. In that case, new buildings are assumed to have a 45% efficiency improvement over old buildings.

The definitions of regions in the two different data sources—(IEA, 2013) and (IEA, 2016a)—and in REMIND are not the same. Thus, we mapped the ETP regions onto REMIND regions, summarized in Table. As can be seen, in some cases, the same mapping was used for different regions—e.g. the AFR and MEA regions were both mapped onto the same region from (IEA, 2013) and (IEA, 2016a). This means that the absolute values of the energy demand scenarios for several regions, including AFR and MEA, cannot be used as such. However, as explained below, it is the relative change between the current policies and strengthened policy scenarios that is transferred to REMIND, so this is an acceptable simplification.
Table S3: Mapping from REMIND regions onto regions in (IEA, 2013) and (IEA, 2016a) in the calculations on heating and cooling in buildings.

| REMIND region | REMIND region definition                                      | Region in (IEA, 2013) and (IEA, 2016a)                  |
|---------------|---------------------------------------------------------------|--------------------------------------------------------|
| AFR           | Sub-Saharan Africa excl. South Africa                        | Non-OECD minus [Brazil, China, India, Russia, South Africa and ASEAN] |
| CHN           | China                                                         | China                                                  |
| EUR           | European Union                                               | European Union                                         |
| IND           | India                                                        | India                                                  |
| JPN           | Japan                                                        | OECD minus [EU, USA and Mexico]                        |
| LAM           | Latin America                                                | Brazil                                                 |
| MEA           | Middle East, North Africa, and central Asia                  | Non-OECD minus [Brazil, China, India, Russia, South Africa and ASEAN] |
| OAS           | other Asian countries mainly located in South East Asia      | ASEAN                                                  |
| ROW           | Rest of the world including among others Australia, Canada, New Zealand, Norway, Turkey, and South Africa | OECD minus [EU, USA and Mexico]                        |
| RUS           | Russia                                                       | Russia                                                 |
| USA           | USA                                                          | United States                                          |
| World         | World                                                        | World                                                  |

S2.2.2 Appliances and lighting

First, final energy consumption for lighting and electrical appliances in the residential and commercial sector was quantified by multiplying the combined shares of “Lighting” and “Appliances and miscellaneous equipments” estimated from the IEA ETP 2016’s 6DS scenario. Because geographical representations differ between the REMIND model and the IEA ETP, a proxy region was identified to estimate the appliances shares in each REMIND region. To estimate the share of appliances and lighting in building sector energy use for the REMIND regions, we applied the same mapping between the REMIND regions and IEA regions as presented in Table.

The final energy consumption for subsector $i$ (= electric appliances and lighting) in country $j$ in year $t$ under the good practice policies scenario ($FE_{GP,i,j,t}$) is calculated using the following equation:

$$FE_{GP,i,j,t} = FE_{NoP,i,j,t} \times \left( \frac{1 - EIR_{Auto,i,j} - EIR_{GP,i}}{1 - EIR_{Auto,i,j}} \right)^{t-BY} \tag{1}$$

where

$FE_{NoP,i,j,t}$: final energy consumption in subsector $i$ in country $j$ in year $t$ under the REMIND current policy scenario;

$EIR_{Auto,i,j}$: Autonomous energy efficiency improvement rate in subsector $i$ in country $j$;

$EIR_{GP,i}$: Additional energy efficiency improvement in subsector $i$ resulting from good practice policies (0.5%/yr);

BY: base year (2018).

In the analysis $EIR_{Auto,i,j}$ was assumed to be 1%/yr for all countries. The results are not sensitive to this parameter; $FE_{GP,i,j,t}$ decreases by only 0.7% when $EIR_{Auto,i,j}$ is increased from 1%/yr to 5%/yr.

To transfer these results to REMIND, we calculated for each region the percentage reduction of total final energy consumption in buildings (SH&C and appliances) between our current policy scenario
and each of the other scenarios. The region-specific relative reduction results were then used in REMIND to set maximum bounds on total final energy use in buildings.

**S2.3 Policy impact calculations for the transport sector**

**S2.3.1 Passenger transport**

The calculations consist of two steps: the application of the enhanced policy to countries, and the harmonisation of results to inputs required for REMIND.

The main data sources for the **first step** are the ICCT Roadmap Model (ICCT, 2012) and its recent updates (ICCT, 2017), which provide the reference development for 16 regions. Our own stock turnover model then adjusts the efficiency of new vehicles according to the enhanced scenarios.

The model assumes a homogeneous age structure in the current vehicle stock and does not differentiate the efficiency between older and newer vehicles in the current stock. Vehicles drop out as they reach the end of their lifetime, and new vehicles fill up the gap to fulfil the projected transportation need (in vehicle-km). We estimate the average lifetime of cars across regions based on the ICCT Roadmap Model (see ICCT (ICCT, 2012), p. 38). The stock turnover model works with a resolution of years.

The starting year for the policy is 2018, meaning that this is the first year where vehicles under the enhanced policies come in. A set share of vehicles is electric, and does not cause any direct emissions. The remaining vehicles comply with the set efficiency standard. Using the ICCT Roadmap model from 2012 and setting the starting year for policies in 2018 causes a gap of 6 years, for which the calculations include no additional policies beyond those already included in the Roadmap. This has an impact on the car stock in the starting year, and thus on the reductions the good practice policies cause.

The stock turnover model provides absolute emissions under the reference development and the enhanced policy scenario for the type of cars evaluated (e.g. light duty vehicles). REMIND uses absolute energy use and the share of electric vehicles in new sales as an input. The **second step** thus converts the results from the stock turnover model to absolute energy use of the complete sector:

The growth of CO2 emissions under the scenarios from the stock turnover model are applied to the energy use of the specific vehicle type (in this case light duty vehicles) in the base year of the ICCT Roadmap (here 2010). Then, the energy consumption of the remaining vehicle types is added. The ICCT Roadmap does not consider any policies beyond 2012, thus instead growth rates from the IEA’s ETP 2016 serve as a proxy for the development of the remaining vehicle types. At the end, the growth of the total transport sector’s energy use is applied to the energy use in the REMIND base year. Wherever we use growth rates, we apply them in 5-year intervals.

Note that some efficiency standards consider electric vehicles as well, thus there is an overlap with the support for electric vehicles which we could not consider quantitatively.

**S2.3.2 Freight transport**

The approach for efficiency improvements in trucks equals that of light duty vehicles (see section S2.3.1). To consider the diversity of trucks to some extent, the stock turnover model calculates the impact on medium heavy-duty trucks (MHDT) (Gross Vehicle Weight Rating (GVWR) of 14 000 to 30 000 lbs) and heavy heavy-duty trucks (HHDT) (GVWR of above 30 000 lbs) separately.
S3. Supplementary Information on the modeling framework

**REMIND-MAgPIE model:** The scenarios in this study have been developed with the coupled REMIND-MAgPIE integrated assessment modeling framework. The coupled framework has been presented in Kriegler et al. (Kriegler et al., 2017), from which the following description is adapted.

The REMIND-MAgPIE integrated assessment modeling framework consists of the energy-economy-climate model REMIND (Bauer, Edenhofer and Kypreos, 2008; Leimbach, Bauer, Baumstark and Edenhofer, 2010; Leimbach, Bauer, Baumstark, Luken, et al., 2010; Luderer et al., 2013, 2015) coupled to the land-use model MAgPIE (Lotze-Campen et al., 2008; Popp, Lotze-Campen and Bodirsky, 2010; Popp, Humpenöder, et al., 2014). REMIND (Regional Model of Investment and Development) is an energy-economy general equilibrium model linking a macro-economic growth model with a bottom-up engineering based energy system model. It covers eleven world regions, differentiates various energy carriers and technologies and represents the dynamics of economic growth and international trade (Leimbach, Bauer, Baumstark and Edenhofer, 2010; Leimbach, Bauer, Baumstark, Luken, et al., 2010; Mouratiadou et al., 2016). A Ramsey-type growth model with perfect foresight serves as a macro-economic core projecting growth, savings and investments, factor incomes, energy and material demand. The energy system representation differentiates between a variety of fossil, biogenic, nuclear and renewable energy resources (Bauer, Brecha and Luderer, 2012; Klein et al., 2014; R. C. Pietzcker et al., 2014; R. Pietzcker et al., 2014; Bauer, Calvin, et al., 2016; Bauer, Mouratiadou, et al., 2016). The model accounts for crucial drivers of energy system inertia and path dependencies by representing full capacity vintage structure, technological learning of emergent new technologies, as well as investment mark-ups for rapidly expanding technologies. The emissions of greenhouse gases (GHGs) and air pollutants are largely represented by source and linked to activities in the energy-economic system (Strefler, Luderer, Aboumahboub, et al., 2014; Strefler, Luderer, Kriegler, et al., 2014). Several energy sector policies are represented explicitly (Christoph Bertram et al., 2015), including energy-sector fuel taxes and consumer subsidies (Schwanitz et al., 2014). The model also represents trade in energy resources (Bauer et al., 2015). A detailed model description can be found at [http://themasites.pbl.nl/models/advance/index.php/Model_Documentation_-_REMIND](http://themasites.pbl.nl/models/advance/index.php/Model_Documentation_-_REMIND)

MAgPIE (Model of Agricultural Production and its Impacts on the Environment) is a global multi-regional economic land-use optimization model designed for scenario analysis up to the year 2100. It is a partial equilibrium model of the agricultural sector that is solved in recursive dynamic mode. The objective function of MAgPIE is the fulfilment of agricultural demand for ten world regions at minimum global costs under consideration of biophysical and socio-economic constraints. Major cost types in MAgPIE are factor requirement costs (capital, labor, fertilizer), land conversion costs, transportation costs to the closest market, investment costs for yield-increasing technological change (TC) and costs for GHG emissions in mitigation scenarios. Biophysical inputs (0.5° resolution) for MAgPIE, such as agricultural yields, carbon densities and water availability, are derived from a dynamic global vegetation, hydrology and crop growth model, the Lund-Potsdam-Jena model for managed Land (LPJmL)(Bondeau et al., 2007; Müller and Robertson, 2014). Agricultural demand includes demand for food (Bodirsky et al., 2015), feed (Weindl et al., 2015), bioenergy (Popp et al., 2011), material and seed. For meeting the demand, MAgPIE endogenously decides, based on cost-effectiveness, about intensification of agricultural production (TC), cropland expansion and production relocation (intra-regionally and inter-regionally through international trade)(Lotze-Campen et al., 2010; Schmitz et al., 2012; Dietrich et al., 2014). MAgPIE derives cell specific landuse
patterns, rates of future agricultural yield increases (Dietrich et al., 2014), food commodity and bioenergy prices as well as GHG emissions from agricultural production (Popp, Lotze-Campen and Bodirsky, 2010; Bodirsky et al., 2012) and land-use change (Humpenöder et al., 2014; Popp, Humpenöder, et al., 2014).

https://redmine.pik-potsdam.de/projects/magpie/wiki/Overview

Emissions in the land-use and energy sectors are interlinked by overarching climate policy objectives and the deployment of bioenergy (Klein et al., 2014; Popp, Rose, et al., 2014; Rose et al., 2014). REMIND and MAgPIE models are coupled to establish an equilibrium of bioenergy and emissions markets in an iterative procedure (Bauer et al., 2014). The atmospheric chemistry-climate model MAGICC (Meinshausen, 2011) is used to evaluate the climate outcomes of the REMIND-MAgPIE emission pathways.

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