Energy needs for adaptation significantly impact mitigation pathways

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Abstract

Climate adaptation actions can be energy-intensive. If households and industries use more energy to cope with the ongoing and expected changes in climate conditions, the mitigation challenge can look inherently different. This adaptation-energy feedback is absent in most of the up-to-date energy scenarios. Here we provide new evidence on how climate change impacts and adaptation can alter mitigation pathways with a focus on the response of residential, commercial, and industrial activities. We quantify the impacts of climate-induced adaptive changes in final energy use on energy investments and costs, emissions, and on air pollution. We find that climate adaptation induces changes in energy demand that have a direct bearing for the energy system as a whole, with non-negligible implications for greenhouse gas emissions and local air pollutants, as more energy capital would be locked-in into fossil fuels. When the energy requirements for adaptation are accounted for, the level of the carbon price needed to achieve mitigation policy goals increases by up to 30%. Adaptation to climate change, as we know it from the empirical evidence of past behaviour of people and industry, bear a high risk of being climate-blind.

Introduction

As the European Union has just launched the new EU Adaptation Strategy aimed at accelerating adaptation while maintaining the commitment to climate neutrality, we still lack a comprehensive characterization of how adaptation actions might actually alter mitigation pathways and costs. When people adjust to experienced or expected changes in climate, their actions often involve modifications of energy expenditures or investments to replace equipment with better adapted items or to purchase new equipment, such as more efficient and effective cooling and heating systems [1]. Many adaptation actions, as we know them from the empirical evidence of past behaviours of people and industry, can be energy-intensive [2, 3]. Water pumping, desalinization, water purification are examples of technologies that will be used more and more to cope with climate-induced water scarcity [4, 5]. Together with the air-conditioning race [6], they could contribute to lock our societies into higher emissions and energy costs [7].

Growing empirical evidence indicates that climate change and more extreme events lead to more electricity being used in summer for space cooling [8, 9, 10], but also for operating appliances for food storage, such as refrigerators [11], and for entertainment, as people might change habits in response to outside meteorological conditions [12]. While the need for space heating, on average, is expected to require less energy [13, 14, 15, 16, 17], the extent and occurrence of cold waves can lead to higher energy consumption [18]. Extreme temperature levels also have a direct effect on labour and capital productivity [19], therefore affecting the energy consumption of industrial and commercial activities as well. The impacts of heat on labor productivity are well-documented [20]. Although shifts in working hours can be an effective adaptation strategy especially for outdoor activities, air-conditioning can reduce production losses for the manufacturing and service sector [21]. The performance of equipment, such as data centers, and the mechanical functioning of machines are also sensitive to the surrounding temperature conditions and high operating temperature can cause electronic components to lose functionality [22].

Climate-change induced changes in energy demand have a direct impact on the energy system as a whole, with an ultimate feedback on climate and the environment. Overall, lower energy demand increases the flexibility achieving low temperature mitigation scenarios, and reduces the need of negative emissions [23]. Considering that the energy sector plays a key role in the energy transition [24], if climate adaptation requires more energy across multiple sectors and activities, the mitigation challenge, including the shape and its economic costs, could look substantially different. Integrated Assessment Models (IAMs) are the tools that most prominently have contributed to the elaboration of energy scenarios and future mitigation pathways [25, 26], and most of them do not account for climate impacts, avoided impacts, and adaptation [27]. Such incomplete integration still remains an important gap in the most recent report of the Intergovernmental Panel on Climate Change [24] and in the recent studies extending the Shares Socioeconomic Pathways (SSPs) to the energy sector [28]. The literature on climate change impacts and energy demand is broad and growing. The sensitivity of energy demand to weather has been documented for a long time by economic and engineering studies [29, 30, 31, 32]. Yet, most up-to-date energy scenarios and mitigation pathways do not include the adaptation-energy feedback into their models [33] and only a very small fraction of studies have conducted broader, integrated assessments using IAMs [3]. Although the literature so far has suggested that the global economy can absorb the adaptation costs induced by rising energy demand [34, 35, 36, 37], we lack an overall understanding of the impacts on the energy system, in the context of the energy transition described in mitigation pathways.

Here, we provide new evidence on how climate change impacts can affect our understanding of global mitigation pathways. We integrate what we call the adaptation-energy feedback loop describing the climate-induced changes in final energy use into the IAM "World Induced Technical Change Hybrid model" (WITCH) [38], and we account for the heterogeneous effects across regions, fuels, and economic sectors. Our results indicate that, if done in a traditional way, adapting to climate change while reducing emissions, as indicated in the currently implemented climate policies, will raise the demand for electricity by 7% (18%) and for fuels by 1% (2.5%) by 2050 (2100). The increase in energy needs leads to more energy capital locked-in into fossil fuels, for an additional 200 Gigawatt (GW) of coal-fired capacity, 250 GW of oil-fired capacity and 520 GW of gas-fired capacity by 2050. Adaptation would imply also more economic resources for grid investments, power generation, and fuel consumption. The carbon price required to reach a certain carbon budget would need to increase, and the cost-effective allocation of emissions over time would also look different compared to a scenario without the adaptation-energy feedback loop. Our study is one of the first to integrate the energy needs for adaptation endogenously into mitigation pathways, highlighting the implications for decarbonization and policy design.

An integrated assessment of the energy needs for adaptation

IAMs quantitatively capture the inter-dependencies among socio-economic, behavioral, technological, and physical drivers of future global and regional pathways for the coupled human-climate system. The WITCH model [38] is a process-detailed IAM that fully integrates the optimization of a top-down representation of the economy, a bottom-up description of the energy system, and a stylized dynamics of the climate, covering several energy sectors, fuels and air pollutants at a macro-regional level (See Methods).

We model the adaptation-energy feedback loop in three steps summarized in Figure 1, where the red highlights indicate the new elements in the modeling framework. First, we empirically estimate a reduced-form relationship between country-level annual average temperature and the annual occurrence of extreme cold ($<$12.5°C) and hot ($>$27.5°C) days using historical data (statistical emulator, see Section S2 in the Supplementary Information). The statistical emulator makes it possible to directly link, and therefore project, the future occurrence of days with extreme temperatures based on the regional temperature level. The latter in turn is statistically related to the global change in annual mean temperature, the variable that is commonly available in climate modules of IAMs (See Methods and Section S1 in the Supplementary Information). Second, we model the direct relationship between changes in the occurrence of extreme temperature days and the demand for electricity, gas and oil in the residential, commercial, and industrial sectors as estimated in [39]. Third, we implement the direct changes in energy demand through (inverse) changes in energy productivity in the production tree of the IAM (See Methods). As the supply-side of the energy sector meets the climate-induced changes in demand, we measure the variation in the costs of power generation, grid infrastructure and fuels' extractions and expenditures. The variation in the use of coal and gas affects the total level of extraction, including domestic extraction and imports.

We examine the implications of the adaptation-energy feedback on mitigation policies (carbon pricing and cost-effective emission allocation) and their co-benefits in terms of air pollution with a cost-effectiveness analysis. The carbon budget is consistent with a predetermined climate target, and implemented via a uniform global carbon price. We focus on climate policies that achieve the goal of keeping global average temperature increases either below 2.5°C, below 2°C, or well-below 2°C compared to the pre-industrial level. Climate targets are therefore achieved in a cost-optimal way, with no international compensations nor carbon emission trading. In the Reference scenario, countries follow their currently implemented climate policies (until 2020), and a similar level of climate ambition is assumed afterwards. Socio-economic assumptions regarding population and output growth follow the middle-of-the-road Shared Socio-Economic Pathway SSP2 [40].

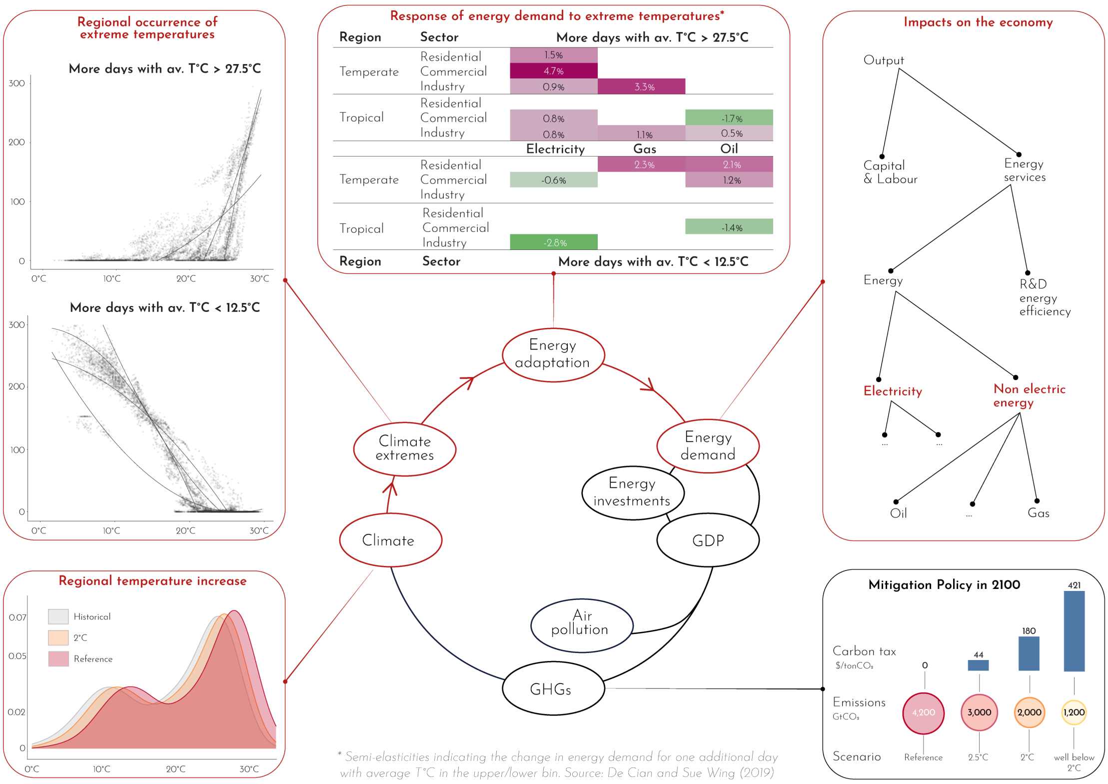

Figure 1: Modelling framework of an integrated approach to the adaptation-energy feedback loop. The circle represents the integrated framework of the WITCH model linking the economy, the energy system, and the climate system. The red lines highlight the components in which new equations have been added to include the adaptation-energy feedback loop. A detailed description of each step and of the methodological advancements is presented in the Methods and Supplementary Methods.

Climate change strongly modifies the regional exposure to warm days

The bi-modal distribution of cold days (<12.5°C) shifts uniformly towards the left around 2100 (2090-2100 average) with respect to the historical (1986-2005 average) in the 2°C and Reference scenarios. The distribution of warm days (>27.5°C) instead exhibits much heavier right tails in the future compared to the historical distribution, especially in the Reference scenario. The bi-modal shape of the distribution reflects differences between tropical (cross marks) and temperate (bubble marks), see Figure 2, Panel a. The increase in the annual number of warm days around 2100 with respect to the historical exceeds the decrease in the annual number of cold days. Most of the countries in the right tail of the additional warm (cold) days' distributions are characterized by a tropical (temperate) climate (Figure 2, Panel b). The Reference scenario entails an increase in the number of warm days and a reduction in the number of cold days, with respect to the 2°C scenario. The projected median number of additional annual warm days with respect to the historical around 2100 is roughly three times larger in the Reference scenario (15 in temperate countries and 33 in tropical countries) than in the 2°C scenario (5 in temperate countries and 12 in tropical countries). The median decrease in annual cold days in temperate countries ranges form 12 to 32, depending on the scenario, while tropical countries are almost unchanged. Within the 17 regions included in the WITCH model, Indonesia, South-East Asia and Sub-Saharan Africa experience the largest increase in annual warm days (reaching up to 100 additional warm days), while Europe, the Middle East and the United States experience the largest decrease in the number of cold days (Figure 2, Panel c).

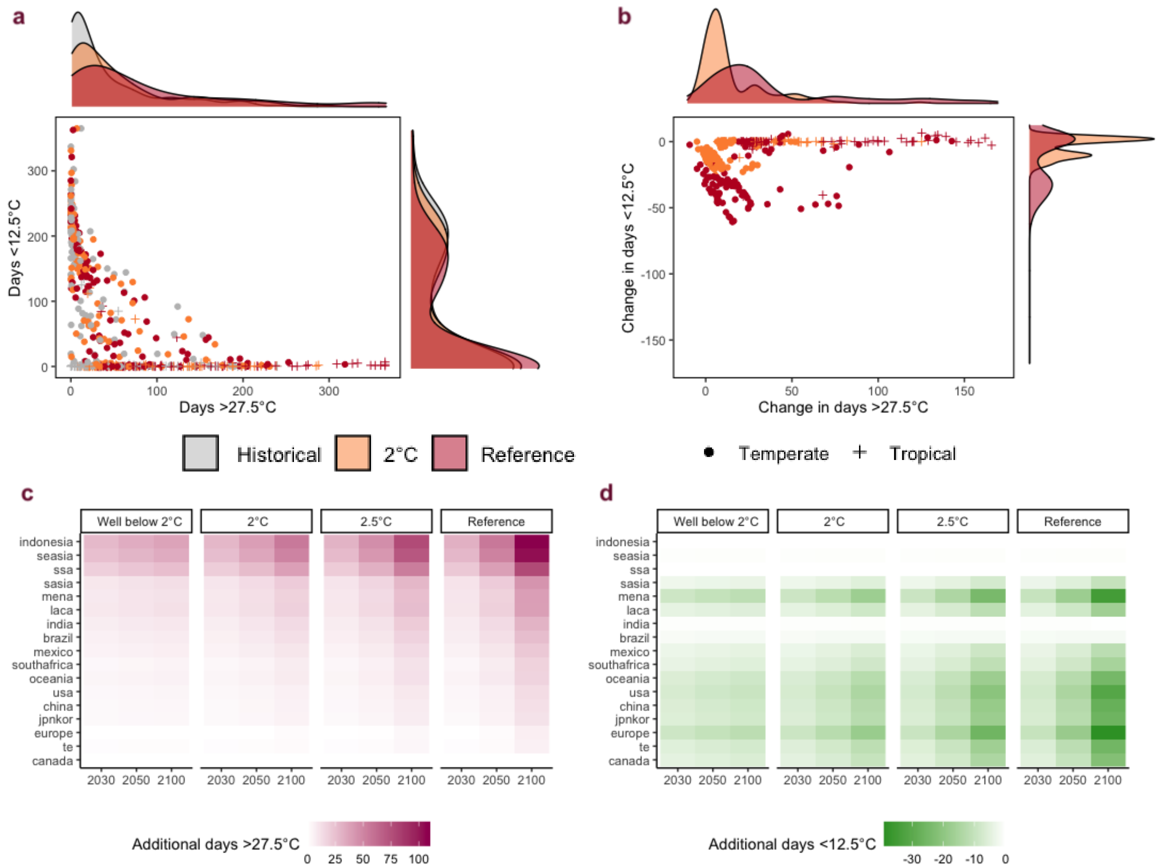

Figure 2: Future changes in the frequency of warm and cold days, historical (1986-2005 mean) and future (2090-2100, ensemble mean of 21 General Circulation Models (GCMs) as in [41]) projected annual occurrence across countries. Panel a: Annual number of days >27.5°C (x axis) and < 12.5°C (y axis) in the historical period and around 2100 under the 2°C and Reference scenarios. Panel b: Difference between the annual occurrence of days under the 2°C and Reference scenarios compared to the historical, around 2100. Markers' shape indicate Tropical (cross) and temperate (bubble) countries, while the distributions refer to the full sample of countries. Panel c - d: Difference in the occurrence of warm (panel c) and cold (panel d) days in the four future scenarios for the 17 regions of the WITCH model around 2030 (2020-2040 average), 2050 (2040-2060 average) and 2100 (2090-2110 average).

Adaptation to future climate change will need more energy

Energy needs for adaptation increase over time and with the degree of global warming. Additional energy demand in buildings (residential and commercial) and industry will rise by 40 exajoule (85 EJ) in 2050 (2100) in the Reference scenarios, with 80% (90%) of that increase being driven by electricity (Figure 3, panels a - c), and the remaining by liquids and gas demand (Figure 3, panels d - e). In relative terms, such requirements correspond to a 7% (18%) increase over the no-adaptation case for electricity and to 1% (2.5%) for liquids and gas demand (henceforth "fuels" demand), resulting in a 2.5% (5%) increase in total final energy demand by 2050 (2100), compared to what the reference energy demand would be without adaptation. Mitigation policies cut the energy requirements for adaptation by more than half. In 2100 the additional adaptation-energy needs remain in the order of +20-50 EJ for electricity, which would correspond to a 6%-12% increase over the no-adaptation case. Adaptation demand for liquids and gas would essentially go to zero. Buildings (residential and commercial activities) account for 60% of the projected increase in electricity demand by 2100 (see Supplementary Figure S2), while the overall increase in the final demand for liquids and gases masks heterogeneous responses across sectors. In 2100, the adaptation of residential and commercial activities leads to a reduction of fuels' final demand by 10 EJ. Industries instead increase the demand for oil and gas by 30 EJ[1].

Africa and the Middle East (MEF) will face the largest increase in energy for adaptation, reaching 23 EJ out of the total 85 EJ in 2100. Electricity demand in the region surges by roughly 40% in the Reference scenario by 2100 (and by 18%

[1]Heating, ventilation, and air conditioning (HVAC) systems used by industrial activities can be divided into comfort related HVAC and continuous or process related HVAC [42]. Comfort related HVAC is related to the thermal comfort of the workers and is typically performed by HVAC installations on building. Continuous or process related HVAC ensures that the operation of manufacturing systems and production processes (e.g. food processing and storage industry) is not undermined by temperature variations. While space cooling in residential buildings is mostly delivered through electricity, industrial and commercial facilities can use fossil-fueled based cooling techniques, such as cooling absorption [43].

in the "Well below 2°C" scenario), while liquids and gas demand increase by up to 15% in 2100, relative to the no-adaptation case. Electricity demand increases by more than 20% in Latin America and by 15% in OECD countries and Asia by 2100. The same regions experience a negligible or negative reduction in fuels' use. Russia shows the lowest increase in electricity demand by 2100 (up to 7%), and a 6% decrease in liquids and gas use in the same year.

The expansion of the power generation fleet necessary to accommodate the additional demand for adaptation consist of a mix of energy sources shaped by the mitigation policies. While in the next few decades the additional power generation installed is carbon-intensive, after 2030 new capacity mostly consists of renewable energy and storage capacity (Supplementary Figure S3). This means that the adaptation-energy feedback would pose new challenges to mitigation that mostly affect the reduction in the energy intensity of the economy, and not so much to the carbon intensity of the electricity mix, which will be decarbonized anyway (Supplementary Figure S4).

In the next decades, if climate policy is not ambitious enough, adaptation needs can lead to additional lock-in into fossil-based generation [44], [45]. Globally, additional 200 GW of new coal-fired capacity, 250 GW of new oil-fired capacity and 520 GW of new gas-fired capacity are installed by 2050. Climate policy will help keep check on the energy mix of the additional generation needed to address adaptation. In mitigation scenarios, the additional oil-fired and coal-fired required by the adaptation-energy feedback by 2050 falls by 50% to 90% from the Reference scenario (in absolute numbers, additional 14 to 17 GW of new coal capacity and 80 to 130 GW of new oil capacity would be required). Additional gas-fired capacity falls more progressively as, depending on the stringency of the climate policy, 110 to 280 GW of new capacity would be required by 2050.

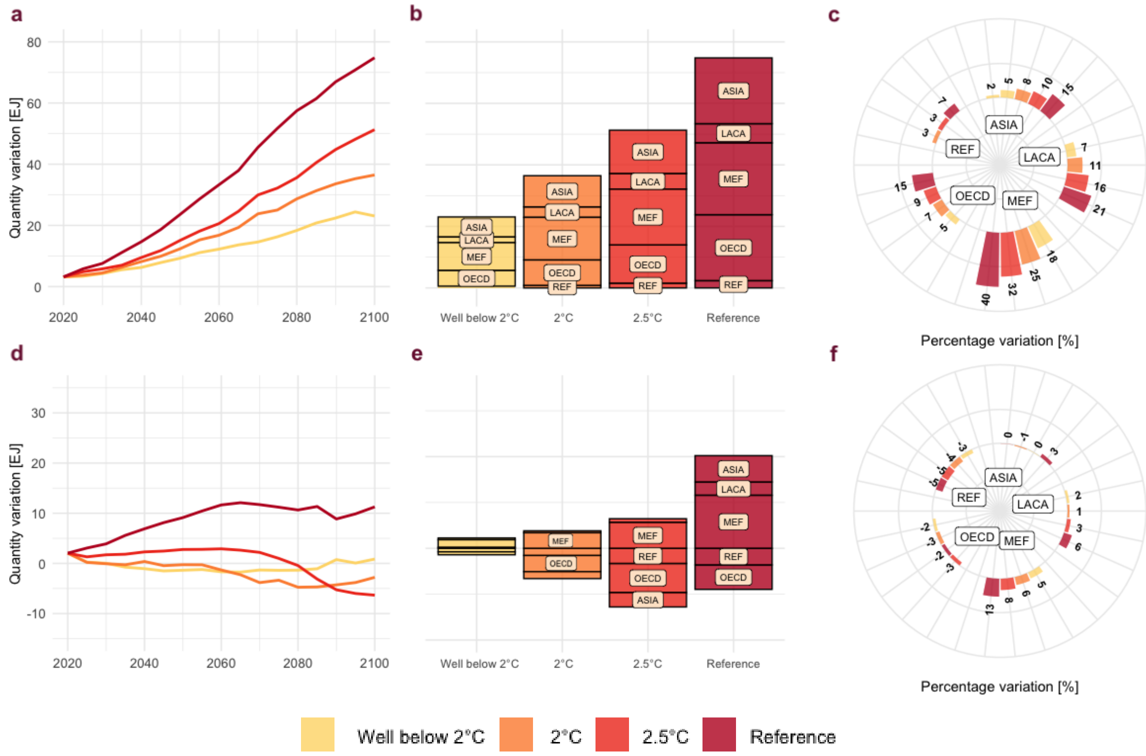

Figure 3: Projected energy for adaptation demand of electricity (panels a - c) and liquid and gas fuels (panels d - e). Panels a and d show the yearly increase in global demand from 2020 to 2100 across the different scenarios. Panels b and e show the regional increase in demand in 2100. Panels c and f show the regional percentage increase of the cumulative additional demand induced by the adaptation-energy feedback. The additional demand of liquids and gas includes both traditional fossil fuels and bio-fuels, as the latter are substitutes of the former.

Ambitious mitigation halves, but does not eliminate, the energy costs for adaptation

Adaptation's impacts on energy demand would also entail higher energy costs. Here we decompose the incremental energy costs into three main components (Figure 4): additional investments in new generation capacity (generation costs, including R&D investments, capital expenditures and the related operation and maintenance expenditures (O&M)), additional grid investments and additional fuel costs (including the investments and O&M costs in fossil fuel extraction and the expenses associated with higher liquids and gas consumption). Additional energy costs are the highest under the Reference scenario, reaching 17 trillion USD in Net Present Value (NPV) between 2025 and 2100 (Figure 4, Panel a). The annual undiscounted additional costs reach 630 billion USD (1.9 trillion USD) in 2050 (2100), a 9% (15%) increase from total energy costs (Figure 4, Panel b). Within the different components, the relative increase in the NPV of costs by 2100 in the Reference scenario is heterogeneous: fuel costs increase by 3.5%, while generation costs by 18% and grid costs by 23%. Ambitious mitigation policies significantly reduce the adaptation energy costs to 10 and 5 trillion USD in NPV, in the 2.5°C and Well below 2°C scenarios, respectively. Resulting annual discounted additional costs range from 220 to 380 (280 to 830) billion USD in 2050 (2100), depending on the stringency of the climate target. Even in the Well below 2°C scenario, the NPV of generation and grid costs by 2100 increase by 7% and 9% respectively.

While energy costs remain significant in the more stringent mitigation scenarios, the composition is quite different compared to the Reference case. Fuel costs become negligible whereas the majority of costs are related to the new investments in power generation, which are about half of total costs in the Reference and almost two thirds of total costs under the mitigation policy scenarios. Each additional megawatt hour (MWh) of energy required to meet adaptation costs between 50 and 80 USD, depending on the mitigation scenario and the year (Figure 4, Panel c). Total costs are the smallest under ambitious mitigation policy, but in the low carbon budget scenarios the costs per unit of additional energy demand peak around 2040, reflecting the higher share of generation costs, which then fall with the decrease in renewable generation costs. Unitary costs in the less ambitious mitigation scenarios are more stable over time, around an average of 70 USD/MWh. The Reference scenario results in relatively low costs per final energy demand of around 60 USD/MWh, but towards the last decades of the century, higher expenses related to fuel consumption brings up the costs again (see Supplementary Figure S5). When moving from the Reference to the policy scenarios, the costs of expanding the power grid to support the increase in power capacity and the additional grid requirements related to the integration of intermittent renewable sources also go down, but at a slower pace compared to the contraction in the final energy demand for adaptation, leading to an increase in the unitary costs for the grid, becoming two times larger (20 USD/MWh) compared to the Reference (10 USD/MWh) scenario in 2050.

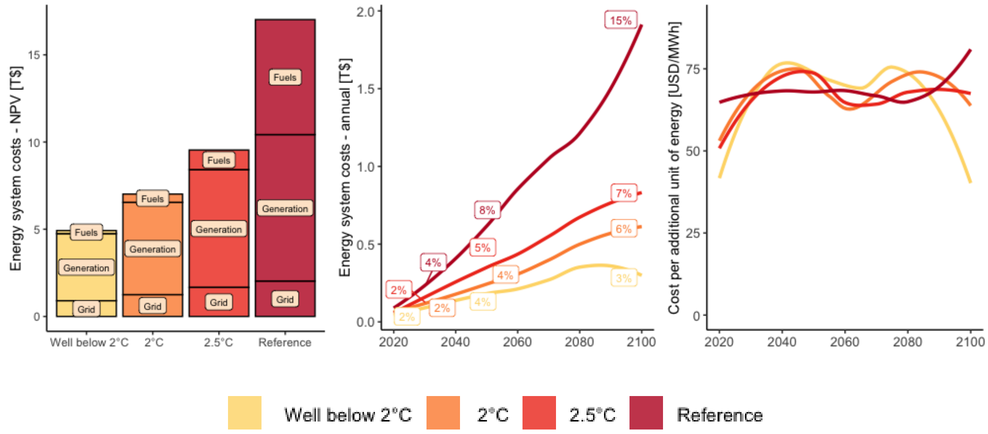

Figure 4: Increase in global energy costs. Panel a: Net Present Value (NPV, using a 3% discount rate) of the additional energy costs incurred up to 2100 including electricity generation, fuel consumption and grid management. Panel b: total annual undiscounted additional energy costs. Labels show the percentage increase with respect to total undiscounted costs without the adaptation-energy feedback. Panel c: annual additional costs per unit of additional final energy demand. Additional refers to the additional demand and costs compared to the corresponding scenarios without the adaptation-energy feedback.

Adaptation directly affects carbon prices

Energy needs for adaptation induce variations in the energy markets that ultimately result in a shift in CO2 emissions from fossil-fuel combustion and heavy industries. The scaling-up of energy demand driven by climate change adaptation contributes to increase cumulative emissions of greenhouse gases, especially towards the end of the century, when it could reach 300GtCO2eq, about 7% of the total cumulative emissions (Figure 5, Panel a). The countries that contribute to the additional cumulative emissions by the largest share are the places where energy demand increases the most, namely developing and tropical regions such as Sub-Saharan Africa, South-East Asia, Middle East and North Africa, Indonesia and India, but also developed economies, such as the United States.

Given this increase in emissions, the adaptation-energy feedback directly affects the level of the global carbon price that is needed to reach the desired carbon budget (Figure 5, Panels b - c). The carbon price increase is highest in the least ambitious scenarios, as it reaches up to 30%, corresponding to a 5 to 8 (13 to 21) USD/tCO2eq increase in 2050 (2100), while it increases by 5% in the most ambitious mitigation scenarios ("Well below 2°C" scenario).

Despite the constraints on the global carbon budget, the geographic heterogeneity in the distribution of the additional energy needs leads to changes in regional emissions (Figure 5, Panel d). Tropical developing regions are characterized by a 5-10 GtonCO2eq increase in cumulative emissions by 2100. OECD countries, China and Russia instead see similar reductions in cumulative emissions. Regional results have a bearing on climate policy design, should a different policy instrument, such as an emission trading schemes with initial allocations of emission reductions, being implemented. Our results indicate that adaptation needs could also affect the cost-effective allocation of emission reduction across regions. Countries with an increase in energy needs would need to receive more permits.

The lock-in of additional energy requirements into fossil-based generation especially in the short-run has direct consequences not only on GHG emissions, but also on air quality (see Figure 5, Panel e). We project a significant increase in nitrogen oxides (NO_x) and sulphur dioxide (SO_2), two of the key air pollutants related to the combustion of coal and oil [46, 47]. Annual emissions go up the most in Sub-Saharan Africa, MENA and South-East Asia, by about 40 kton/year (NO_x) and by 70 kton/year (SO_2), corresponding to a percentage increase of of 5% and 27%, respectively.

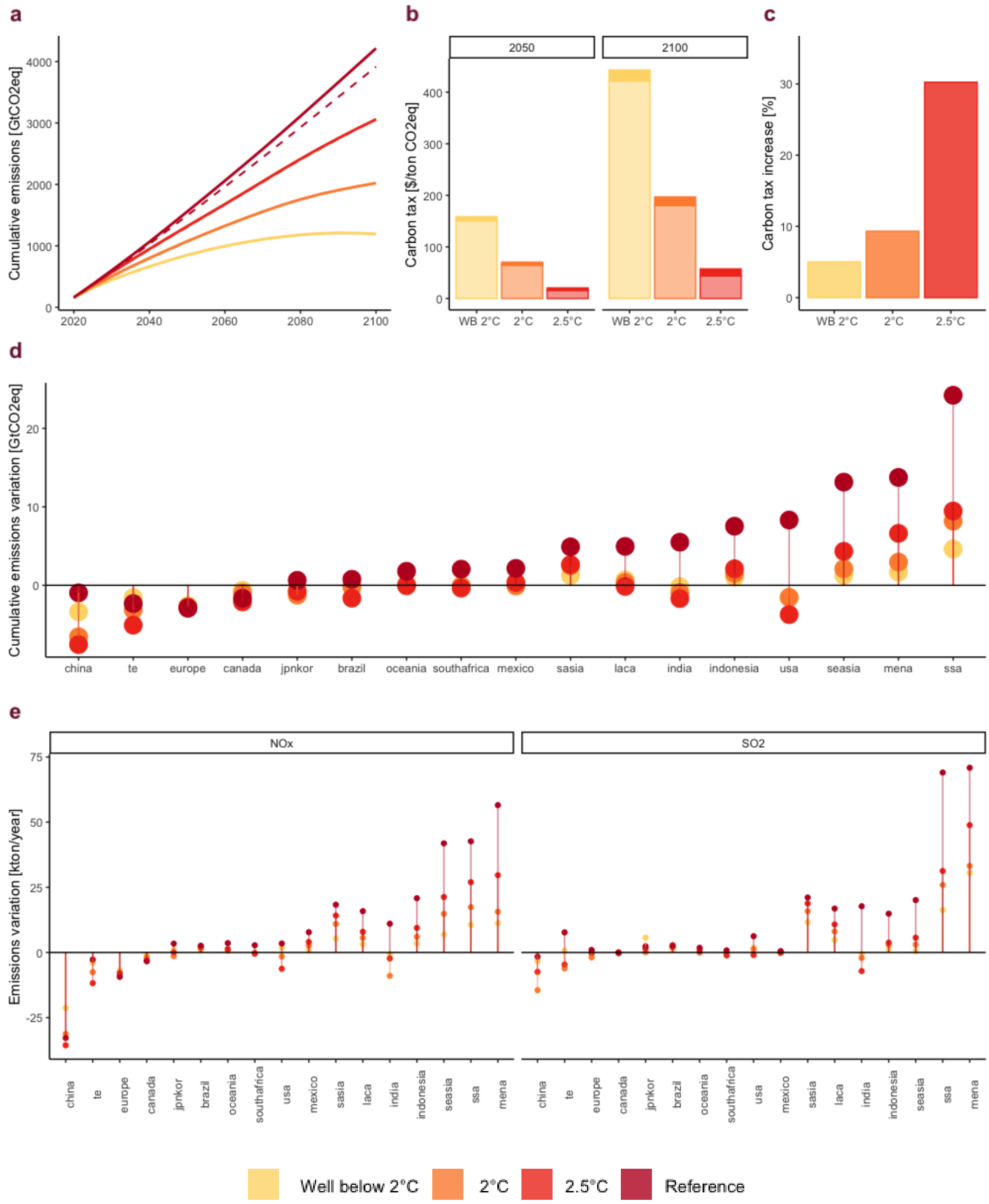

Figure 5: Variation in the cumulative CO_2 emissions and in the carbon tax. Panel a: Cumulative CO_2 emissions up to 2100 with (solid lines) and without (dotted lines) the energy-adaptation feedback. Panel b: Carbon tax in the mitigation scenarios. The increment in the carbon tax due to the energy-adaptation feedback is represented by the stacked bars in full colours. Panel c: Average annual percentage increase in the carbon tax. Panel d: Variation in the regional cumulative emissions in 2100. Panel e: Average annual variation in the pollutants' emissions across world regions over the period from 2020 to 2100.

Discussion and conclusions

Including the feedback of climate change impacts and adaptation in energy scenarios is key for understanding how the effectiveness of mitigation options might be affected [48]. This paper provides a first account of how adaptive responses to climate change affect energy demand and energy costs, indicating how the design of cost-effective mitigation policies could change. Our results provide an end-point quantification that is in line with more aggregated cost-benefit models [49, 50], showing that mitigation lowers adaptation needs in terms of additional economic resources, but also in terms of additional energy demand.

Our simulated net increase in buildings' global energy demand and the projected baseline investments required to transform the energy system fall within the estimates of previous studies (see Supplementary Figure S6 and Supplementary Figure S7). Even with an incomplete feedback mechanism, limited to the adaptive behaviours of residential, commercial, and industrial activities through the use of energy, we find evidence that adaptation directly affects the shape and the costs of mitigation pathways, as both energy system costs and carbon prices increase significantly. The increase in energy system costs due to climate-adaptation projected in this study are in line with bottom-up regional regional models focusing on the United States [2].

If the ambition of mitigation policy does not rise rapidly, climate adaptation needs can actually contribute to further exacerbate the risk of lock-in into polluting fossil-fuel-based generation in the next few decades. The additional final energy demand and the resulting energy costs are cut by 50% when aiming at the 2.5°C target and by up to 75% when reaching the target of Well Below 2°C. Nevertheless, even in the Well-Below 2°C target, energy needs for adaptation may rapidly affect the energy system transition, as an additional 10 EJ (20 EJ) of energy demand would be required annually by 2050 (2100). Climate adaptation furthermore interacts with the co-benefits of mitigation policies, as the new fossil-fuel-fired generation would

[2] We project a +5% increase in generation, fuel and grid costs in the US under the Reference scenario by 2050 (or +2 Trillion USD in NVP), a shock which is in line with the projected increase in generation and fuel projected in 2050 in the multi-model study by [51], ranging from +2% (GCAM) to +10% (ReEDS model).

be an important additional source of air pollution.

Ignoring the energy system costs and the environmental implications attributable to rising adaptation needs in Integrated Assessment Models results in an underestimation of the benefits of mitigation policies. Developing new scenarios that bring more evidence on the tangible positive side-effects of policies can help accelerate the tightening of the emission reduction targets within the framework of the Paris Agreement and help avoid the potential vicious cycle of energy for adaptation including up-scaling of vicious behaviors, such as massive adoption of air conditioners.

The potential tension between mitigation and adaptation would be much more significant if the integrated approach proposed in this paper were expanded to include other mechanisms through which responses to climate change affect energy demand [3], such as activities related to water supply, transportation and cooling chains. More research broadening the field of investigation to a wider set of adaptation actions at the global scale is required in order to better inform future climate policy aimed at resilient climate neutrality.

Future work could improve the characterization of the heterogeneous responses of energy demand to meteorological conditions by accounting for the non-linear response across the full distribution of daily temperatures, adopting regional-specific thresholds in the computation of climate extreme indices or by accounting for humidity, all aspects that can influence the resulting projections, especially in tropical regions [52]. Depending on the energy efficiency of the newly purchased equipment as well as on the magnitude of appliances' penetration in the future, new capital stock may attenuate or amplify the energy requirements of future adaptation, such as the demand response to cold and warm days [39, 53]. Power generation and transmissions are also vulnerable to climate change (see [54] for a recent review), and therefore fully characterizing the interaction between mitigation and adaptation requires integrating demand-side and supply-side impacts.

Methods

THE IAM APPROACH. WITCH is a dynamic global model that fully integrates a simplified representation of the economy, the energy system, and the climate system. The economy is modelled through an inter-temporal optimal growth model. A representative agent chooses consumption to maximize regional welfare, and consumption decisions are related to investments choices. The energy sector is hard-linked with the rest of the economy and energy investments and resources are chosen optimally together with the other macroeconomic variables. A climate model (MAGICC) computes the future changes in global average temperature on the basis of the GHG emissions generated by the economic and energy system. A fully integrated module translates the regional emissions into global temperature through atmospheric concentrations. Another module links the global temperature increase to changes in regional temperature based on a linear downscaling of country-level mean temperature estimated using future warming scenarios (Representative Concentration Pathways, RCPs, see Section 1 in the Supplementary Methods). WITCH is integrated with an air pollution module, FASST(R), a source-receptor model based on the TM5-FASST model developed by JRC-Ispra, that computes the annual concentrations of several pollutants, namely SO2, NOx, fine Particulate Matter (PM2.5) and O3. The fine PM 2.5 concentrations include Particulate Organic Matter (POM), secondary inorganic PM, dust and sea-salt. The FASST(R) model produces concentrations on a world spatial grid of resolution of 1 degree by 1 degree and has been previously used in other studies to assess premature death from air pollution exposure [55, 56].

MODELING ADVANCEMENTS. The adaptation - energy feedback loop is implemented with a set of equations linking the occurrence of extreme temperatures to energy demand. Our Extreme Temperature Indicators (ETIs) are defined as the yearly count of days in which average temperatures fall above the threshold of 27.5°C and below the threshold of 12.5°C, respectively. The regional future realization of the ETIs is defined for climatic clusters, c, as:

$$ETI_{i,t} = f(T_{c\in i,t}, T^2_{c\in i,t}) \tag{1}$$

where

i regions (17 regions)

t time step in the model, 2005-2100

.

The reduced-form relationship (eq. 1) takes the form of a polynomial function (f) of yearly mean temperatures (T_c) varying across climatic clusters. The equation is estimated from a panel econometric model based on yearly, country level observations covering 180 countries from 1970 to 2010 (see section 2 in the Supplementary Information).

The transmission of the climate shock to the economy is modelled through the sector-specific semi-elasticities of energy demand to ETIs estimated in [39]. Following [39], our calibration values for the transmission of the climate shock in the commercial and industrial sectors in tropical economies reflect the extensive use of distributed petroleum-fired generators to satisfy final electricity demand.

Sectoral (residential, commercial and industry) semi-elasticities ($\beta_{i,f,s}$) are aggregated based on the share of the final energy demand of each sector over total final energy demand ($\lambda_{i,f,s,t}$), for each fuel and over time. The share is computed from the baseline model projections in each 5-years time step. The aggregation allows to compute a set of semi-elasticities ($\beta_{i,f,t}$) specific to each region (i), energy vector (f) and year (t).

$$\overline{\beta}_{i,f,t} = \sum_{s} \lambda_{i,f,s,t} \beta_{i,f,s} \tag{2}$$

where

i regions (17 regions)

t time step in the model, 2005-2100

f energy vector (electricity EL, non-electric energy GAS and OIL)

s sectors (residential, commercial, industrial)

The historical and future realizations of the ETIs are combined with the long-run semi-elasticities in order to identify the climate-induced shock on energy demand ($\Phi_{f,i,t}$):.

$$\Phi_{f,i,t} = \frac{exp(\sum \overline{\beta}_{i,f,t} ETI_{i,t})}{exp(\sum \overline{\beta}_{i,f} ETI_{i,0})} - 1 \tag{3}$$

where

i regions (17 regions)

t time step in the model, 2005-2100

f energy vector (electricity EL, non-electric energy GAS and OIL)

We follow [57] and assume climate-induced energy demand shocks affect the productivity of the energy inputs entering into the aggregate production function. If climate-induced shocks increase energy demand, it is as if the economic systems needed more energy to produce output. If climate-induced shocks reduce energy demand, it is as if the economic systems needed less energy to produce output. Climate-related positive shocks (e.g. increase in energy demand) are therefore modeled as technological retrogression requiring more inputs to generate a given output.

In the WITCH model, energy (EN) is a combination of electricity (EL) and non-electric energy (NEL), which includes coal, gas, and oil. Electricity and non-electric energy can be substituted with an elasticity of substitution described by the parameter ρ_{EN}:

$$EN_{i,t} = [\tilde{\alpha}_{EL,i} EL_{i,t}^{\rho_{EN}} + \tilde{\alpha}_{NEL,i} NEL_{i,t}^{\rho_{EN}}]^{\frac{1}{\rho_{EN}}} \tag{4}$$

In our new formulation, the productivity of electricity and non-electricity are an endogenous function of the climate shocks:

$$\tilde{\alpha}_{EL,i,t} = \alpha_{EL,i} \frac{\Phi_{EL,i,t} Q_{EL,i,t}}{\sum_f Q_{f,i,t}} \tag{5}$$

$$\tilde{\alpha}_{NEL,i,t} = \alpha_{NEL,i}\left[\frac{\Phi_{GAS,i,t}Q_{GAS,i,t}}{\sum_f Q_{f,i,t}} + \frac{\Phi_{OIL,i,t}Q_{OIL,i,t}}{\sum_f Q_{f,i,t}}\right] \quad (6)$$

QUANTIFICATION OF ENERGY COSTS. Power generation costs ($C\_GEN_{i,t}$), include the investments in generation capacity ($I_{i,t,j}$), R&D investments in power generation technologies ($I\_RD_{i,t,j}$) and O&M costs ($OM_{i,t,j}$):

$$C\_GEN_{i,t} = \sum_j (I_{i,t,j} + I\_RD_{i,t,j} + OM_{i,t,j}) \quad (7)$$

where
i regions (17 regions)
t time step in the model, 2005-2100
j power generation technology

The fuel costs ($C\_FUEL_{i,t}$) include the investments and O&M costs in fossil fuel extraction ($OM\_ex_{i,t,f}$) and the expenses associated with liquids and gas consumption ($EXP\_ff_{i,t,f}$):

$$C\_FUEL_{i,t} = \sum_f (OM\_ex_{i,t,f} + EXP\_ff_{i,t,f}) \quad (8)$$

where
i regions (17 regions)
t time step in the model, 2005-2100
f fuel

The investment in the electrical grid ($I\_GRID_{i,t}$) are computed based on grid capital. The grid capital stock is adjusted taking into account a linear relationship between grid capacity and the capacity of traditional power generation technologies, as well as the investments for the integration of variable renewables' generation. A detailed description of is available in [38].

SCENARIOS. In the Reference scenario, CO_2 emissions targets are based on extrapolating the implied ambition levels of current climate policies until 2020. Overall, the Reference scenario leads to carbon budget of about 4,200 GtCO2. More stringent mitigation scenarios are designed to achieve the carbon budgets of 3,000, 2,000, and 1,200 GtCO2 (measured from 2018 until the year of net-zero CO2 emissions) in the 2.5°C, 2°C, and well-below 2°C, respectively. Non-CO2 greenhouse gases in these scenarios are priced equivalently to the implied CO2 prices, using 100-year global warming potentials for conversion. We use explicit GHG pricing and climate stabilization targets are achieved in a global cost-optimal way, with no international compensation scheme or carbon emission trading.

Population forecasts [58] and country-level GDP projections implemented using Purchasing Power Parities (PPP) [59] are based on the basic and extended SSPs [40]. We focused on a socio-economic development in line with the Shared Socio-Economic Pathway Middle-of-the Road (SSP2), which is essentially a continuation of the historical trends. For more information on the implementation of key aspects such as energy productivity, land-use and power technologies and fossil fuel resources see [38].

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Contributions

E.D.C. posed the initial research questions to frame the study. All authors developed the energy-adaptation feedback loop and carried out the analyses of results. J.E. and G.M. ran the integrated assessment model. F.C. and E.D.C. led the writing of the manuscript, with all other authors contributing.

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