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Will adaptation delay the transition to clean energy systems?

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Abstract

Climate change is one of the greatest environmental challenges facing our planet in the foreseeable future, yet, despite international environmental agreements, global GHG emissions are still increasing. In this context, adaptation measures are an alternative to mitigation efforts. These measures involve adjustments to economic or social structures to limit the impact of climate change without limiting climate change itself. To assess the interplay of adaptation and mitigation, we propose AD-MERGE, an integrated assessment model that includes both reactive ("flow") and proactive ("stock") adaptation strategies as well as several mitigation (energy) technologies. We find that adaptation delays but does not prevent the transition to clean energy systems (carbon capture and sequestration systems, nuclear, and renewables). Moreover, applying both strategies is more effective than using just one. *Keywords:* Climate change; Climate policy mix; Adaptation; Mitigation; Integrated assessment

1 Introduction

Climate change is one of the greatest environmental challenges facing our planet in the foreseeable future. According to the Intergovernmental Panel

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on Climate Change (IPCC), climate change is expected to impact both ecosystems and the environmental services they provide (e.g., biodiversity) and human societies (e.g., affecting human health). This is expected to result in economic damage of approximately 2%[1] of GDP per year for a temperature increase of 2.5°C (Arent et al., 2014).

To address this issue, one strategy is the mitigation approach, which aims to reduce anthropogenic greenhouse gas (GHG) emissions. To be effective, such a strategy needs to be implemented by the major emitters. The Kyoto Protocol to the United Nations Framework Convention on Climate Change (United Nations, 1997) set emission reduction targets for the developed countries. More recently, the Copenhagen Accord (United Nations, 2009) has recognized the importance of drastically reducing GHG emissions to limit the global temperature rise to 2°C, but without setting binding emission-reduction targets. Despite these agreements, global GHG emissions continue to increase, adding to atmospheric GHG concentrations (Victor et al., 2014).

An alternative strategy is the use of adaptation. Adaptation measures adjust economic or social structures to limit the impact of climate change without limiting climate change itself. They can be implemented in an array of sectors and can take on many forms. Examples include crop modifications in agriculture, the building of sea walls, and medical precautions against pandemics. We can distinguish between two types of adaptation strategies (Smit et al., 2000; Lecocq and Shalizi, 2007). Reactive strategies (or "flow" adaptation) are measures implemented in reaction to existing concerns. Proactive strategies (or "stock" adaptation) are preventive measures that must be taken in advance. Adaptation has a number of advantages over mitigation. First, many adaptation measures have immediate benefits, whereas most mitigation benefits occur after several decades. Second, mitigation needs global cooperation to be effective, whereas adaptation can generally be implemented regionally. Adaptation also has some disadvantages. For higher increases in temperature, the uncertainty range of the expected damage is larger (Adger et al., 2005). Mitigation limits climate change and hence limits the uncertainty, whereas adaptation shields us from the impact of climate change without affecting temperature. Furthermore, adaptation itself is likely less effective at higher temperatures.

Until recently, the focus in the climate-change literature and policy arena has been on mitigation. Adaptation is now attracting more attention, both in the scientific community with increased research and in the policy arena

[1] With an uncertainty range of 0% to 2.5%.

where funding has been made available (Pielke et al., 2007). Prominent examples are the IPCC's Fifth Assessment Report, which has four chapters that analyze adaptation, including Chambwera et al. (2014), and the Adaptation Fund[2], which supports adaptation projects in developing countries. Addressing climate change effectively will require a combination of mitigation and adaptation. One way to find the optimal balance of the two approaches is to use an integrated assessment approach that combines social economic elements with geophysical and environmental elements.

Examples of integrated assessment models (IAMs) include DICE (Nordhaus, 1994, 2014), FUND (Anthoff and Tol, 2013), MERGE (Manne et al., 1995; Manne and Richels, 2005), RICE (Nordhaus and Yang, 1996; Nordhaus, 2011), and WITCH (Bosetti et al., 2006). Mitigation policies have been widely studied with IAMs, but adaptation strategies have only recently been explored. The first model to include adaptation was the PAGE model (Hope et al., 1993; Hope, 2006, 2009). PAGE modeled adaptation in a simplistic manner: for a small adaptation fee 90% of the climate-change damage could be eliminated. Later models have included a more comprehensive approach to adaptation. We distinguish these models based on the type of adaptation that they include. Several models include only reactive adaptation, such as early versions of AD-DICE (de Bruin et al., 2009b) and AD-RICE (de Bruin et al., 2009a). FEEM-RICE (Bosello, 2008) and the first version of Ada-BaHaMa (Bahn et al., 2012) include only proactive adaptation. Other models include both reactive and proactive adaptation, such as later versions of AD-DICE (de Bruin and Dellink, 2011), AD-RICE (de Bruin, 2011, 2014), and Ada-BaHaMa (Bahn et al., 2015), as well as AD-WITCH (Bosello et al., 2010, 2013). AD-WITCH also includes adaptive capacity, where GDP growth enhances a region's capacity to adapt. The FUND model also includes sector-specific adaptation options, which depending on the sector are either proactive or reactive.

The aim of this paper is twofold. First, we contribute to the adaptation literature, which relies on a limited number of IAMs, by introducing in the MERGE model both reactive and proactive adaptation. In the process, we also recalibrate the MERGE damage function. Second, we use the resulting model (AD-MERGE) to study in detail the impact of adaptation on the implementation of mitigation measures in the energy sector. Such analyses are possible because MERGE includes a distinct energy module that details different technological options to curb energy-related GHG emissions. In terms of adaptation modeling, AD-MERGE includes the latest devel-

[2]See www.adaptation-fund.org.

opments in the literature. In terms of mitigation modeling, AD-MERGE provides a more detailed representation of mitigation options than existing IAMs provide. In the DICE/RICE approach, energy use and the corresponding emissions are directly derived from economic production, and mitigation options are aggregated into a single mitigation cost function. Ada-BaHaMa distinguishes between a "carbon" sector and a "carbon-free" sector, where mitigation consists of replacing the former sector with the latter. AD-WITCH includes a bottom-up representation of the energy sector that distinguishes among seven energy technologies, whereas AD-MERGE has a more detailed representation with close to 40 technologies. Moreover, as far as we know, AD-WITCH does not perform cost-benefit analyses of climate policies. Therefore, it does not allow for the investigation of optimal mitigation policies and the effects adaptation strategies may have on them. AD-MERGE thus enables a more comprehensive analysis of the impact of adaptation on specific mitigation technologies.

The remainder of this paper is organized as follows. In Section 2, we describe the main characteristics of the MERGE model and describe the damage module; we disuss the adaptation options and the calibration of the module. Section 3 presents the numerical results, and Section 4 provides a sensitivity analysis. Section 5 gives a discussion and a comparison with existing studies, and Section 6 presents concluding remarks.

2 Model description

2.1 MERGE description

The Model for Evaluating the Regional and Global Effects of GHG Reduction Policies (MERGE) distinguishes among nine geopolitical regions: Canada, Australia and New Zealand (CANZ); China; Eastern Europe and the Former Soviet Union (EEFSU); India; Japan; Mexico and OPEC (MOPEC); the USA; Western Europe (WEUR); and the rest of the world (ROW). MERGE is composed of four interlinked modules that enable an integrated assessment of climate policies.

The first module (ETA) describes the energy supply sector of each region using a bottom-up engineering approach. More precisely, ETA distinguishes between electricity generation and the production of nonelectric energy (fossil fuels, synthetic fuels, hydrogen, and renewables). GHG emission reduction can be achieved by substitution between electricity generation technologies (e.g., using renewable power plants instead of fossil plants) and nonelectric energy carriers (e.g., switching to low-carbon fossil fuels).

The second module (MACRO) describes the other economic sectors using a top-down macroeconomic (Ramsey–Solow) approach. MACRO relies on a nested constant elasticity of substitution (CES) production function that includes as production factors capital, labor, and electric and nonelectric energy. MACRO captures economic feedback between the energy supply sector and other economic sectors in particular through energy prices that respond to climate policies.

The resulting regional ETA-MACRO models maximize the net present value of regional consumption (i.e., regional welfare). Each region has initial endowments of capital, labor, and fossil fuels (considered as exhaustible resources). MERGE links the regional ETA-MACRO models by aggregating the regional welfare functions into a Negishi weighted global welfare function. A balanced international trade of oil, gas, energy-intensive goods, and an aggregate good in monetary units (the "numéraire" good) further links the regional ETA-MACRO models.

Furthermore, the ETA-MACRO models compute the anthropogenic emissions of the main GHGs, namely CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide), HFCs (hydro-fluorocarbons), and SF_6 (sulfur hexafluoride). The third module, the climate module, describes how GHG emissions contribute to GHG concentrations in the atmosphere and how these in turn affect atmospheric temperatures through changes in radiative forcing.

Finally, the last (damage) module quantifies the economic losses caused by temperature changes. It considers both market damage (valued by market prices) and nonmarket damage (estimated by a willingness-to-pay approach). In this paper, we have replaced the original market damage function of MERGE with a new function based on the AD-RICE damage module that integrates reactive and proactive adaptation; see Section 2.2 below.

2.2 Adaptation and damage modeling

The original MERGE model includes both market and nonmarket climate change damage. For market damage, MERGE assumes that a 2.5°C temperature increase will yield an economic loss of 0.25% of GDP in high-income regions and 0.5% in low-income regions. Furthermore, market damage increases proportionally with temperature. For nonmarket damage, MERGE assumes a willingness to pay the equivalent of 0.8% of consumption in high-income regions and 0.4% in low-income regions to avoid nonmarket damage associated with a 2.5°C temperature increase. A quadratic relationship between temperature increase and nonmarket damage is assumed.

In AD-MERGE, we retain the nonmarket damage of the original MERGE model, but we replace the market damage function with a series of functions describing climate damage. Our damage description includes the use of adaptation as a policy option to reduce damage. This new damage module is based on the AD-RICE-2012 model[3] (de Bruin, 2014). We distinguish between gross damage, which represents damage before adaptation, and residual damage, which represents damage after adaptation. Gross damage as a percentage of output ($GD_{j,t}$) is defined for each region j and each time period t as a function of the temperature change (T):

$$GD_{j,t} = \alpha_{1,j} T_t + \alpha_{2,j} T_t^{\alpha_{3,j}}. \tag{1}$$

This is the most commonly used form for damage costs in IAMs, where $\alpha_{1,j}$, $\alpha_{2,j}$, and $\alpha_{3,j}$ are calibration parameters, with $\alpha_{3,j}$ generally taking a value between 1 and 3 (Tol et al., 1998). Residual damage as a percentage of output ($RD_{j,t}$) is a function of total adaptation ($PT_{j,t}$) and gross damage ($GD_{j,t}$):

$$RD_{j,t} = \frac{GD_{j,t}}{1+PT_{j,t}}. \tag{2}$$

The functional form of Eq. (2) has been chosen because it limits between 0% (without any adaptation) and 100% (with infinite adaptation) the amount by which the gross damage can be reduced. This functional form also ensures decreasing marginal benefits of adaptation, i.e., the more adaptation is used, the less effective additional adaptation will be. This is because more cost-effective measures will be applied first.

AD-MERGE distinguishes between reactive and proactive adaptation. These two forms can have different characteristics and hence should be modeled differently. Reactive adaptation occurs as a reaction to an experience of climate change. For example, farmers may notice that rainfall patterns are changing and adjust their crop planting times to optimize the harvest. The main characteristic of reactive adaptation is that we assume that its costs and benefits fall within the current period and have no effect in the next period, i.e., reactive adaptation is a flow variable. This form of adaptation is often undertaken by individuals and does not need large investment, so it can be considered autonomous[4] and private. Proactive adaptation on the other hand is undertaken in anticipation of climate change. For example,

[3]Note that we do not include catastrophic and sea level rise damage (which are included in the RICE model) because we assume that these elements are represented by MERGE's nonmarket damage.

[4]Autonomous adaptation refers to adaptation undertaken by individuals autonomously without government or other intervention.

one may build a seawall in anticipation of a rise in the sea level. The necessary investment (costs) will pay off in the future (benefits). Furthermore, the investment builds up a stock of adaptation, which has an impact in future periods too (just as a capital stock does). Because of the large-scale nature of proactive adaptation, it can be considered public.

Proactive and reactive adaptation are aggregated using a CES function, as follows:

$$PT_{j,t} = \beta_{1,j} \left(\beta_{2,j}\, SAD^{\rho}_{t,j} + (1-\beta_{2,j}) FAD^{\rho}_{t,j}\right)^{\beta_{3,j}/\rho} \tag{3}$$

where $\beta_{1,j}$, $\beta_{2,j}$, and $\beta_{3,j}$ are calibration parameters; $SAD_{t,j}$ is the total quantity of adaptation capital stock; $FAD_{t,j}$ is the amount spent on reactive adaptation; and ρ is given by $\frac{\sigma-1}{\sigma}$ with σ the (constant) elasticity of substitution; see de Bruin (2014) for more details. This elasticity is chosen to reflect the observed relationship between the two forms of adaptation, which are imperfect substitutes, with ρ set to 0.5. Adaptation capital stock is built up as follows:

$$SAD_{j,t+1} = (1-\delta_k) SAD_{j,t} + IAD_{j,t} \tag{4}$$

where δ_k is a depreciation rate and $IAD_{j,t}$ are the investments in adaptation stock. We set δ_k to the value used for the capital depreciation rate in the RICE model. The total adaptation costs ($PC_{j,t}$) in each period are hence the sum of the reactive adaptation costs and the investments in stock adaptation:

$$PC_{j,t} = FAD_{j,t} + IAD_{j,t}. \tag{5}$$

The market damage is the sum of the residual damage and the adaptation costs, and this damage function is calibrated to replicate the net damage computed by the RICE/AD-RICE damage function:

$$D_{j,t} = RD_{j,t} + PC_{j,t}. \tag{6}$$

We calibrate the adaptation costs and benefits based on the adaptation literature as described in de Bruin (2011). Specifically, we used the AD-RICE regional adaptation costs and benefits to calibrate the parameters of the gross damage function (Eq. (1)) and the adaptation function (Eq. (3)). Table 1 shows the calibrated regional gross damage in AD-MERGE.

3 Numerical results

This section presents our policy scenarios, which apply different adaptation strategies, as well as the results of our analyses.

δT	USA	WEUR	JAPAN	CANZ	EEFSU	CHINA	INDIA	MOPEC	ROW
1°C	0.14%	0.15%	0.06%	0.14%	0.10%	0.19%	0.55%	0.35%	0.31%
2.5°C	1.59%	1.25%	0.52%	1.25%	0.99%	2.18%	2.16%	2.43%	1.70%

Table 1: Regional gross damage (in % of GDP) as function of temperature increase.

3.1 Scenario characterization

The AD-MERGE database corresponds to version 5 of the MERGE model with two important exceptions: i) some key parameters of the climate module correspond to the revision of Bahn et al. (2011); and ii) the damage module has been revised and recalibrated as explained in Section 2.2.

The database is characterized by a rich description of the regional energy sectors, with many mitigation options. In terms of electricity-generation technologies, the model considers four types of coal power plants (two with carbon capture and sequestration, i.e., CCS); one type of oil power plant; three types of gas power plants (one with CCS); a generic low-cost renewable power plant (hydroelectric)[5]; a power plant using existing nuclear technology[6]; and a generic advanced "high-cost" power plant. The advanced plant is called LBDE. It relies on biomass, nuclear, solar, and/or wind[7] and corresponds to a "backstop" technology with unlimited capacity. In terms of nonelectric energy supply, the model considers 24 options: the direct use of coal; 10 cost categories for oil supply; 10 cost categories for gas supply; synthetic fuels; a limited supply of low-cost renewables (such as ethanol from biomass); and an unlimited carbon-free supply of nonelectric energy. The carbon-free energy is called LBDN. It is defined in a generic way; this could refer for instance to hydrogen production using carbon-free processes.

The energy production costs are assumed to decline at an exogenous rate of 0.5% per year, except that for the LBDE and LBDN technologies, only a fraction of the cost is exogenously reduced. The remainder of the cost is reduced through the accumulation of knowledge in manufacturing and operation, which is measured by the cumulative installed capacities. This corresponds to the modeling of endogenous technological progress following

[5]This technology has limited capacity reflecting the (limited) potential of the low-cost renewables that it represents.

[6]This technology also has limited capacity, reflecting the current public acceptance of this energy carrier. The model also considers advanced nuclear energy power plants through a generic technology that does not have a limited capacity.

[7]This corresponds to the modeling philosophy of MERGE that avoids *picking specific winners* (Manne and Richels, 2004) among advanced carbon-free technologies, but it does not allow for a distinction between nuclear and renewable energies.

a learning-by-doing approach (LBD); see for example Kypreos and Bahn (2003) and Manne and Barreto (2004).

We have analyzed several scenarios using AD-MERGE. The first is an artificial *Baseline* (used for comparison only), where there is no climate change damage and consequently GHG emissions are not limited. This scenario assumes a world population level of 8.7 billion by 2050 and 9.5 billion by 2100. Between 2000 and 2100, the world GDP increases by a factor of 11 (to 382 trillion USD 2000), whereas primary energy supply and carbon emissions increase by a factor of 4 (to around 1600 EJ/year and 27 Gt C, respectively). In terms of primary energy supply and CO_2 emissions, our baseline scenario closely corresponds to the *high baseline emission* RCP8.5 scenario (van Vuuren et al., 2011). In the following four scenarios, there is climate change damage and the regions react using different climate strategies following a cost-benefit approach. In these policy scenarios, mitigation is possible, but adaptation may be available only on a limited basis. Specifically, we consider a no-adaptation (*NoA*) scenario, where adaptation is not possible; a *Proactive* scenario, where only proactive adaptation is available; a *Reactive* scenario, where only reactive adaptation is available; and a full-adaptation (*FullA*) scenario, where both forms of adaptation are available.

3.2 Temperature and emission paths

Figure 1 presents the temperature increases (from the 2000 level). The temperature increases by almost 2.5°C by 2110 in the Baseline and by approximately 1.8°C in the other scenarios, with slightly higher values when adaptation is possible. Note that all the scenarios miss the target of the Copenhagen Accord, which is an increase of 2°C compared to preindustrial levels[8].

Figure 2 displays the world energy-related CO_2 emission paths that drive the temperature variations. In the policy scenarios, the implementation of mitigation options (discussed in Section 3.4) yields a peak in emissions by 2040 at around 9 Gt C. In the NoA scenario, where mitigation is the only policy available, a rather fast decarbonization path brings the emissions down to 3.1 Gt C by 2110. When adaptation is available, the start of the fast reduction path is delayed by about 20 years. In the corresponding scenarios, the emission levels are reduced to around 4 Gt C by 2110. In other words,

[8]The temperature increase between the preindustrial and the 2000 levels is estimated at 0.6°C (IPCC, 2014).

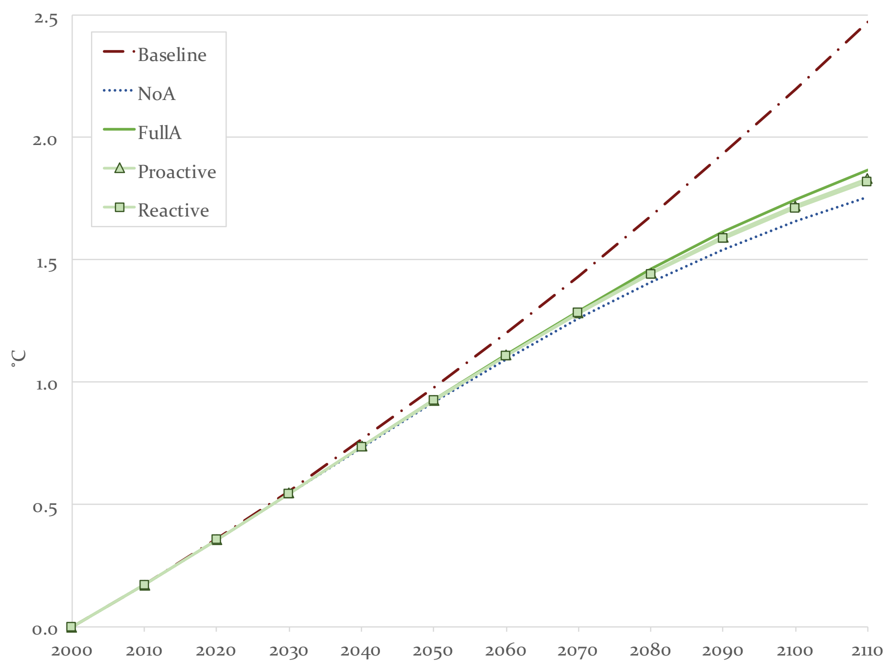

Figure 1: Temperature increase (from 2000).

adaptation delays but does not prevent a (fast) transition toward low-carbon energy systems; see also Section 3.4.

3.3 Damage costs and adaptation measures

Figure 3 gives the global adaptation costs as a percentage of world GDP for our scenarios. It highlights some important trends. First, the adaptation costs increase over time with temperature increase; see again Fig. 1. Second, due to a slowdown in the temperature increase in the 22nd century, adaptation spending increases more slowly by the end of the 21st century. This trend appears earlier with proactive adaptation spending (compared to reactive), due to the delayed effect of the former adaptation. Third, when only one form of adaptation is available (in the Proactive and Reactive scenarios), the fraction of GDP spent on that specific form increases compared to the case where both forms are available (in FullA, indicated by the dashed

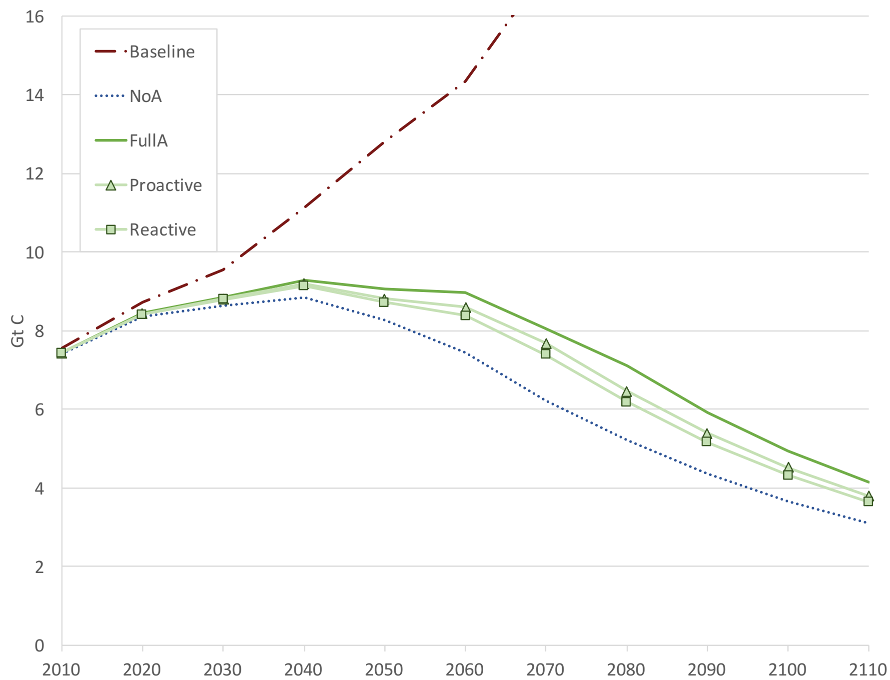

Figure 2: World energy-related CO_2 emission trajectories.

lines "Full-adapt. (IAD)" and "Full-adapt. (FAD)"). However, there is less overall adaptation spending. This is because the two forms of adaptation are imperfect substitutes. Adaptation will thus be less cost-effective when only one form can be applied, and less adaptation will occur.

To illustrate the damage-reducing potential of adaptation, Table 2 presents the adaptation levels for the different regions in the FullA scenario, given as a percentage of the gross damage reduced through adaptation. Regional differences in the adaptation levels are quite large (up to 30%), reflecting adaptation possibilities that vary across regions. Moreover, these levels represent the optimal adaptation, as computed by the model. In reality, lower adaptation levels may be expected, especially in regions currently under development, because of the many constraints on adaptation not explicitly taken into account by AD-MERGE. In particular, lower income regions are likely to have less proactive adaptation, which entails large-scale funding

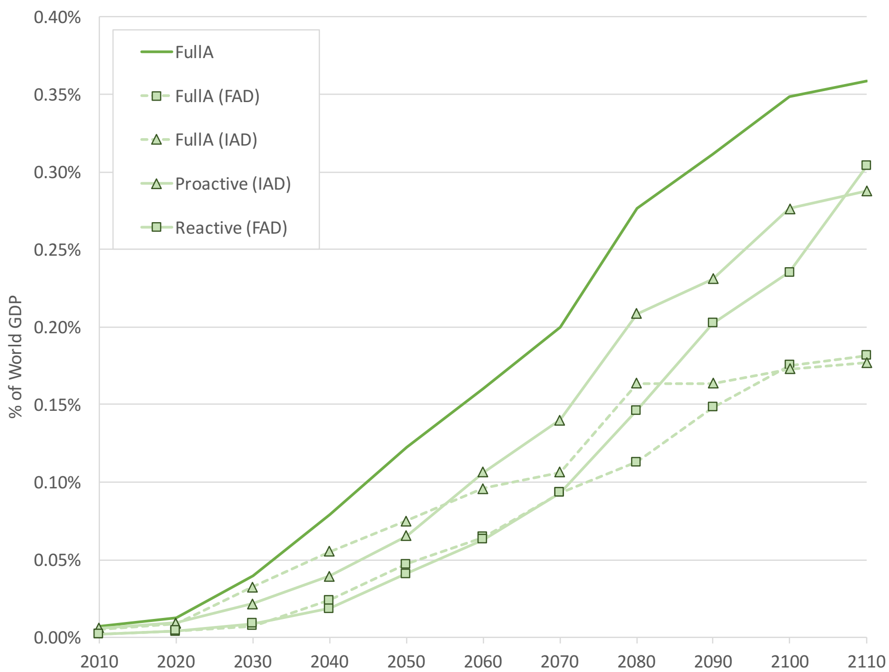

Figure 3: Total adaptation costs (proactive and/or reactive) over time, in % of world GDP. In the FullA scenario, the cost decomposition between proactive and reactive adaptation is given respectively by the dashed lines “FullA (IAD)” and “FullA (FAD)”.

and government planning (de Bruin and Dellink, 2011).

The net climate change damage (residual damage plus adaptation costs) is shown in Fig. 4. The damage increases over time at a steeper rate than the temperature, due to the nonlinear relationship between temperature and damage. The damage associated with temperature change in the Baseline has been computed ex-post and is reported for comparison, reaching around 3.4% in 2110. A comparison of the Baseline and NoA scenarios shows that curbing GHG emissions can significantly reduce damage (to about 1.9% in 2110) by limiting temperature increase. Damage can be further reduced through adaptation, with reactive adaptation being slightly more effective than proactive. Applying both forms of adaptation leads to the lowest damage path (a level of about 1.4% in 2110), despite the slight temperature increase (see again Fig. 1) due to adaptation substituting for some mitiga-

Year	USA	WEUR	JAPAN	CANZ	EEFSU	CHINA	INDIA	MOPEC	ROW
2050	43%	14%	36%	15%	30%	35%	22%	35%	17%
2100	57%	42%	68%	46%	48%	51%	39%	61%	41%

Table 2: Regional adaptation levels in the FullA scenario for 2050 and 2100, in % of gross damage reduced.

tion measures.

Figure 4: Net damage (sum of adaptation costs and residual damage), in % of world GDP.

3.4 Mitigation strategies

Figure 5 presents the world primary energy use in 2010 (for reference), 2050, and 2100. We will comment only on the 2100 situation, where the differences among the scenarios are the greatest, discussing both the total energy use and the energy mix.

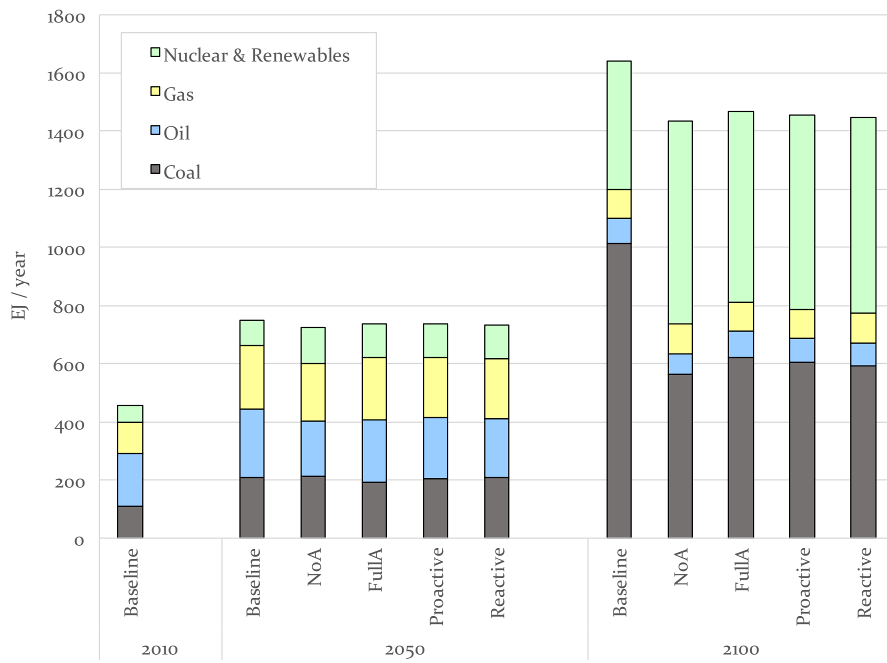

Figure 5: World primary energy use.

Compared to the Baseline, the other scenarios, which include damage that yields GDP losses, require less energy to be supplied to the economy: the reductions are similar and vary between around 10% (in FullA) and 12% (in NoA). Furthermore, there are changes in the energy mix. In the Baseline, energy use is dominated by fossil fuels (especially coal, with a share of 62%). In the policy scenarios, GHG reduction is achieved (at the primary energy level) by the two following means. The first is an increased use of nuclear and renewables[9], mostly at the expense of coal: the share of nuclear and renewables varies between 45% in FullA and 49% in NoA. NoA has a higher share because of the stronger need to curb emissions in the

[9]Recall that MERGE does not distinguish between these two energy carriers.

absence of adaptation in order to reduce damage. The second is inter-fossil substitution, mostly from coal to gas, again more so in NoA. Note also that in all the policy scenarios, coal is mainly used to generate electricity in power plants equipped with CCS systems (see below).

To illustrate the regional differences in primary energy use, Fig. 6 presents the primary energy supply in 2100 for the different scenarios and three groups of regions. Following a World Bank classification[10], these groups are defined as follows: *high income* refers to the OECD regions (USA, WEUR, CANZ, and JAPAN); *middle income* refers to EEFSU, CHINA, and MOPEC; and *low income* refers to INDIA[11] and ROW. The level of total primary energy use is highest in middle-income countries and lowest in high-income regions. Concerning the energy mix, the main differences among regions (across scenarios) is the share of nuclear and renewables. This ranges from 43% for middle-income regions in the FullA scenario and 50% for low-income regions in the NoA scenario. These differences are mainly due to regional energy endowments and adaptation possibilities (in the scenarios where adaptation is available).

To further characterize the mitigation measures undertaken, Tables 3 and 4 present world electricity generation (by power plant type) and non-electric energy production (by energy carrier) in 2100, respectively.

Compared to the Baseline, the mitigation strategies consist mainly, in all policy scenarios, of replacing coal power plants without CCS (COAL-N) by advanced coal power plants with CCS (COAL-A and IGCC).[12] Concerning nonelectric energy, the mitigation strategies are again rather similar with or without adaptation. Compared to the Baseline, the use of fossil fuels and especially synthetic fuels (SYNF) is much reduced in favor of advanced high-cost clean carriers such as hydrogen (LBDN)[13]; in the absence of adaptation, this effect is slightly more pronounced.

[10]See http://data.worldbank.org/about/country-and-lending-groups.

[11]In the World Bank classification, India is a lower-middle income country. We group low income and lower-middle income together as low-income countries.

[12]Note that in all the scenarios, HYDRO and NUC are used at their full capacity by 2100.

[13]Note that in all the scenarios, traditional renewables such as biomass (RNEW) are used at their full potential by 2100.

	Baseline	NoA	FullA	Proactive	Reactive
LBDE	1	2	2	2	2
HYDRO	3	3	3	3	3
NUC	3	3	3	3	3
GAS-A	0	5	0	1	2
COAL-A	0	52	44	50	50
IGCC	6	16	27	21	20
GAS-N	10	8	10	10	10
COAL-N	80	0	0	0	0
Total	103	89	90	90	90

Table 3: World electricity generation (in PWh per year) by power plant type: LBDE (advanced high-cost carbon-free technologies such as advanced nuclear, biomass, and solar), HYDRO (hydroelectric, geothermal, and other existing low-cost renewables), NUC (existing nuclear technology), GAS-A & COAL-A & IGCC (advanced gas and coal plants respectively with CCS), GAS-N (advanced gas combined cycle without CO_2 recovery), and COAL-N (pulverized coal plant without CO_2 recovery).

	Baseline	NoA	FullA	Proactive	Reactive
LBDN	172	417	374	386	395
RNEW	196	196	196	196	196
SYNF	160	0	0	0	0
GASNON	36	27	33	33	28
OILNON	88	69	91	86	82
CLDU	57	26	37	31	31
Total	710	735	732	732	733

Table 4: World nonelectric energy production (in EJ per year) by energy carrier: LBDN (advanced high-cost clean carriers such as hydrogen produced using carbon-free processes), RNEW (low-cost renewables such as ethanol from biomass), SYNF (synthetic fuels), GASNON (gas for nonelectric use), OILNON (oil for nonelectric use), and CLDU (coal for nonelectric use).

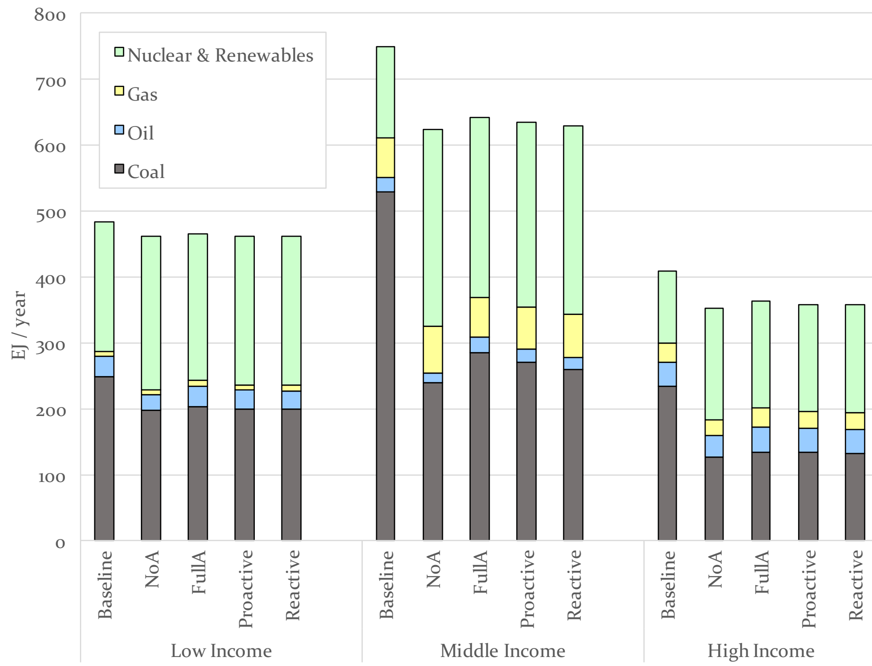

Figure 6: Regional primary energy use.

4 Sensitivity analysis

This section presents a sensitivity analysis of our results. Specifically, we examine how varying the climate sensitivity and the effectiveness of adaptation impacts the interplay of adaptation and mitigation strategies, comparing the FullA and NoA scenarios.

4.1 Climate sensitivity

There remains a high level of uncertainty concerning the precise temperature effect of GHG emissions. To analyze this, we explore different levels of climate sensitivity (CS), following Bahn et al. (2011). We consider our original parameterization with medium CS[14] (3°C) and a mean lag for ocean

[14]The CS parameter corresponds to the long-term equilibrium temperature for a doubling of preindustrial atmospheric GHG concentrations.

warming[15] (57 years), a case with low CS (1.5°C) and a short lag (45 years); and a case with high CS (4.5°C) and a long lag (77 years). The resulting temperature increases for these cases under the FullA and NoA scenarios are given in Fig. 7. The temperature differences between the two scenarios increase slightly with CS: 0.03°C by 2110 for low CS, 0.11°C for medium CS, and 0.15°C for high CS.

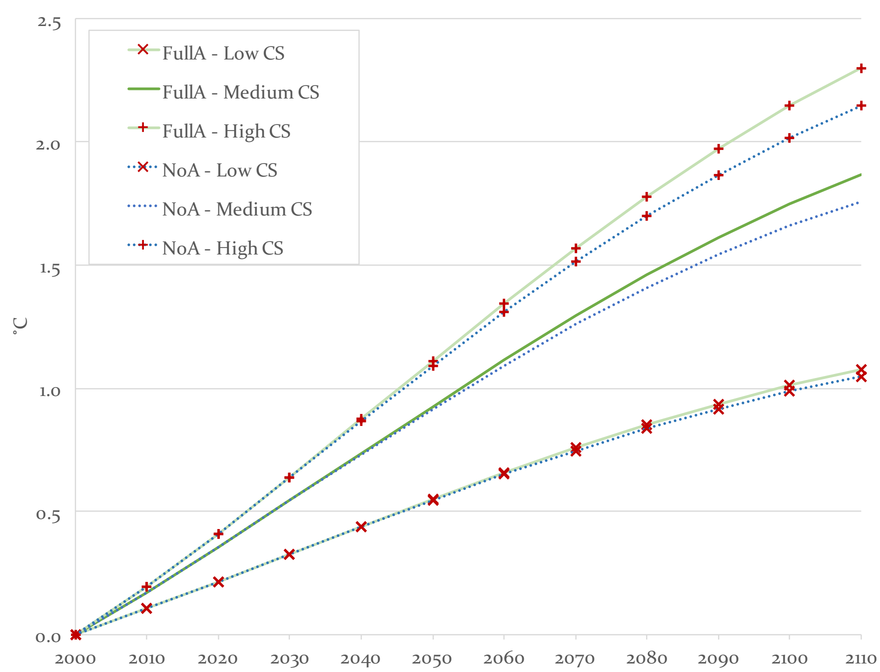

Figure 7: Temperature increase for low, medium, and high CS levels in the FullA and NoA scenarios.

The temperature variations are driven by GHG emissions (CO_2, in particular). Again, the differences between the FullA and NoA scenarios increase with CS. In particular, under high CS, world energy-related CO_2 emissions reduce to 1.9 Gt C by 2110 in NoA and to 3.1 Gt C in FullA (a

[15] This parameter corresponds to the lag between the observed surface temperature and the equilibrium temperature. It is essentially controlled by the uptake and transport of heat by the global ocean circulation.

level comparable with that of the NoA scenario under medium CS). However, in this case, adaptation delays by only 10 years the transition toward cleaner energy systems (compared to 20 years in our original medium CS case). The emission levels are driven by the mitigation efforts undertaken, in particular in the energy sectors. Figure 8 presents the global primary energy consumption. In the long run (2100), both the total energy consumption and the energy mix vary notably with and without adaptation under high CS. Without adaptation, the higher temperature increase would trigger higher damage in the NoA scenario. This yields a greater need for mitigation. Nuclear and renewables then become the dominant primary energy sources by 2100 with a share of 83% (compared to 49% in FullA). One of the main differences is the dominant use of the LBDE technology for electricity generation instead of coal power plants with CCS (IGCC and COAL-A). The considerable introduction of LBDE in NoA is associated with cost reductions for this advanced learning technology due to the (long-run) effects of endogenous technological progress. Cost reductions (in the long run) for electricity generation also induce higher primary energy use in NoA compared to FullA.

4.2 Adaptation effectiveness

Since this paper investigates the influence of adaptation on mitigation choices, it is important to also investigate the sensitivity of our results to the parameterization of adaptation. To assess this, we vary parameter $\beta_{1,j}$ from Eq. (3), which reflects the effectiveness of adaptation. Compared to our original setting, we choose a lower (respectively, higher) adaptation effectiveness (AE) such that the same adaptation costs will result in a 50% lower (respectively, higher) adaptation level (fraction of gross damage reduced). We return to our original (medium) CS setting. Table 5 presents the adaptation levels in 2100 for the different regions in the FullA scenario for our three AE cases. As expected, the levels for each region vary significantly with the AE.

AE	USA	WEUR	JAPAN	CANZ	EEFSU	CHINA	INDIA	MOPEC	ROW
Low	25%	7%	47%	8%	18%	20%	11%	23%	5%
Medium	57%	42%	68%	46%	48%	51%	39%	61%	41%
High	82%	62%	78%	67%	70%	74%	59%	84%	61%

Table 5: 2100 regional adaptation levels in the FullA scenario for low, medium, and high AE levels, in % of gross damage reduced.

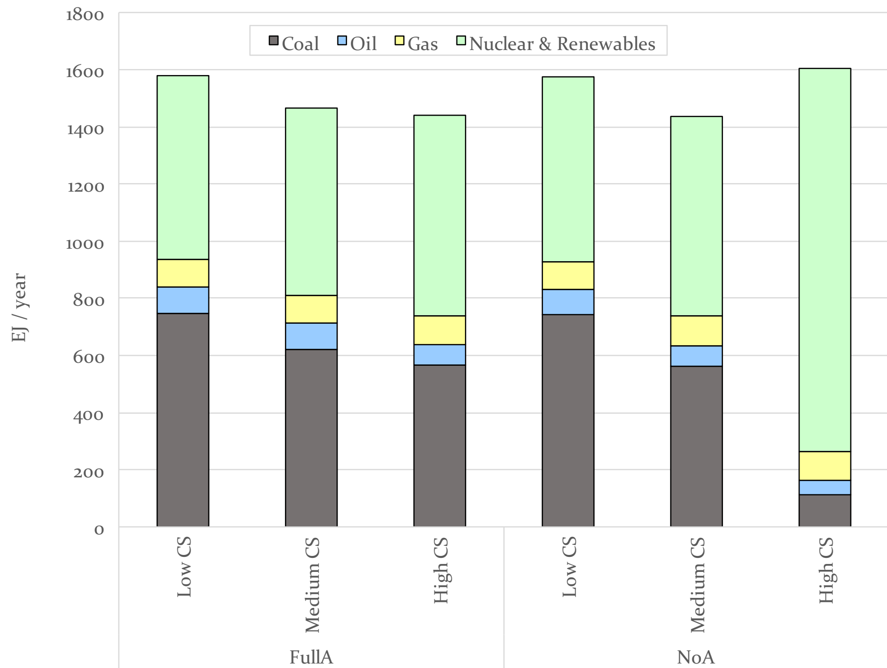

Figure 8: Global primary energy use for low, medium, and high CS levels in the FullA and NoA scenarios.

Higher AE levels reduce mitigation needs: by 2100, world energy-related CO_2 emissions are 3.5 Gt C for low AE (compared to 3.1 Gt C in NoA), 4.1 Gt C for medium AE, and 4.5 Gt C for high AE. In all these cases, adaptation delays by 20 years the transition toward cleaner energy systems (compared to NoA). However, for low AE, the emission path is closer to that of the NoA scenario. Figure 9 presents the global primary energy consumption. In contrast to CS, AE has less impact on primary energy. The main difference is the use of nuclear and renewables: their share is 47% for low AE (compared to 49% in NoA), 45% for medium AE, and 43% for high AE.

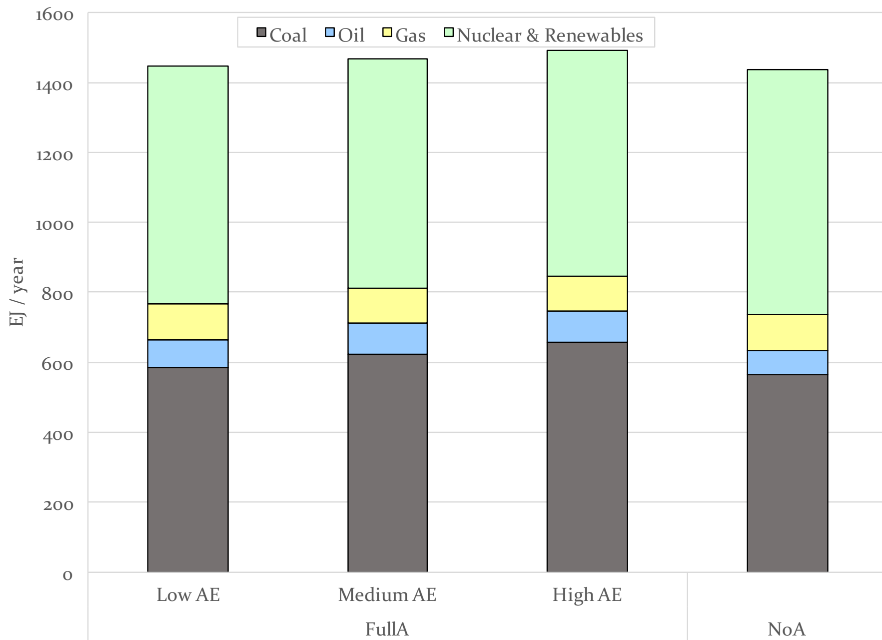

Figure 9: Global primary energy use for low, medium, and high AE levels in the FullA and NoA scenarios.

5 Discussion

It has been argued (e.g., Pindyck, 2013; Stern, 2013) that the uncertainties surrounding climate change render current IAMs useless. There is indeed much uncertainty involved in estimating the relationships between climate, the economy, and energy use. IAMs typically run one or two centuries into the future, making (long-term) assumptions and estimations very uncertain. In AD-MERGE specifically, many forms of adaptation have been aggregated and included. However, the representation of adaptation in the model will obviously not fully replicate all the options available. We believe however that with a cautious interpretation of the results, IAMs can yield useful insight into long-term climate change polices.

Only two other IAMs include explicit adaptation measures and mitigation options: Ada-BaHaMa and AD-WITCH. AD-WITCH has a detailed description of different energy carriers and technologies, but this does not feature in the analyses reported by Bosello et al. (2010, 2013). These studies set a stabilization target for GHG concentrations. When adaptation is applied, GDP increases (through reduced damage), translating into higher energy demands, thus leading to slightly higher mitigation costs to achieve the same target. There is no further discussion of which energy technologies are used to reach the concentration target. In Ada-BaHaMa, as reported by Bahn et al. (2015), adaptation delays the start of the transition toward clean energy systems by 10 years (2055 instead of 2045). Afterward, the transition occurs rapidly as in the case where only mitigation is possible. In AD-MERGE, adaptation delays the rapid transition toward low-carbon energy systems by 20 years (2060 instead of 2040), as reported in Fig. 2 for the FullA scenario in our standard parametrization.[16] After 2060, the transition occurs at the same speed as in the case where only mitigation is possible (NoA scenario). In our sensitivity analyses, we find that adaptation always delays the transition by 20 years, except under high CS where the delay is only 10 years. The finding that adaptation delays but does not prevent the transition toward clean energy systems thus appears robust.

Recalling once more the many uncertainties inherent to IAMs, we recommend interpreting the results of AD-MERGE with caution. We can however make some general policy conclusions based on our analysis. First, adaptation and mitigation are important components of an optimal climate policy. They are imperfect substitutes, and an optimal policy should include both. Second, an emphasis on adaptation (as in the high AE case) could lead to a situation where the use of mitigation options is reduced. Most IAMs assume an optimal adaptation level. Therefore, these models may understate the optimal mitigation, given that adaptation levels are bound to be suboptimal because of the many real-world constraints (de Bruin and Dellink, 2011). Third, although adaptation can considerably reduce climate change damage, a transition toward clean energy systems (clean coal power plants as well as nuclear and renewable technologies) is still warranted in the long run. Indeed, our results show that even with optimal adaptation such systems will be adopted on a large scale, albeit with a delay of up to two decades compared to the situation where adaptation is not available. Given the real-world constraints on adaptation and the high uncertainties involved in assessing climate change effects, an early transition to clean energy systems seems warranted.

[16] Recall however that emissions peak by 2040 in all the policy scenarios.

6 Conclusion

This paper has examined the interactions between adaptation and mitigation policies using an IAM approach. Only a few IAMs include both mitigation and adaptation, and to date there has been no detailed analysis of the interaction between these strategies. Our contribution is the exploration of different mitigation technologies and how adaptation may affect their deployment. To do this, we have proposed the AD-MERGE model based on the MERGE and AD-RICE models. AD-MERGE includes close to 40 energy technologies as well as reactive and proactive adaptation.

Our results show that the optimal levels of reactive and proactive adaptation (and hence adaptation costs) increase over time, as temperature increases. By the end of the century, however, mitigation efforts will reduce the rate of the temperature increase and hence the use of adaptation strategies. This shows the trade-off between mitigation, which limits temperature increases in the long run, and adaptation, which reduces the damage for a given temperature increase and is effective in the short run.

We find that either mitigation or adaptation will significantly decrease the impact of climate change. The best approach is to apply both strategies. Our results also show that proactive adaptation is more effective than reactive adaptation.

Concerning energy use, our results show that, when there is no damage (in our artificial Baseline), fossil fuels (especially coal) dominate the total primary energy supply. When only mitigation strategies are used, there is a transition to CCS systems, nuclear, and renewables. When adaptation is applied in combination with mitigation, this transition still takes place but is delayed by up to 20 years. In other words, adaptation may delay investment in mitigation options, but a transition to low-emitting energy systems appears inevitable in the long run. Our sensitivity analyses show that the configuration of the energy system is quite sensitive to the CS parameter but less so to the AE parameter.

Although we have conducted sensitivity analyses and compared our results to existing studies, our findings should be interpreted with caution. IAMs are complex and inherently include many uncertainties. AD-MERGE could be improved: we could, for example, develop better damage estimates and enhance the treatment of uncertainty. Our results are not definitive, but they may be indicative of future adaptation and mitigation interaction.

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