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Evaluation of climate change impacts on energy demand

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ABSTRACT

Although previous climate change research has documented the effects of linking mitigation and adaptation in the energy sector, there is still a lack of integrated assessment, particularly at national level. This paper may contribute to fill this gap, identifying the interactions between climate change and the energy demand in Macedonia.

The analyses are conducted using the MARKAL (MARKet ALlocation)-Macedonia model, with a focus on energy demand in commercial and residential sectors (mainly for heating and cooling). Three different cases are developed: 1) Base Case, which gives the optimal electricity production mix, taking into account country's development plans (without climate change); 2) Climate Change Damage Case, which introduces the climate changes by adjusting the heating and cooling degree days inputs, consistent with the existing national climate scenarios; and 3) Climate Change Adaptation Case, in which the optimal electricity generation mix is determined by allowing for endogenous capacity adjustments in the model. This modeling exercise will identify the changes in the energy demand and in electricity generation mix in the Adaptation Case, as well as climate change damages and benefits of the adaptation.

1. Introduction

Recently, significant climate change research efforts have been dedicated to linking mitigation and adaptation in energy sector in order to support adoption of a pertinent energy and climate change policy. Hence, a number of studies at national and regional level have analyzed the possible change of energy demand for heating and cooling due to climate change (temperature changes) [1–5]. Also, there has been an attempt to describe energy demand for heating and cooling in the context of climate change at a global scale [6,7]. However, very few of these studies take into account the socio-economic implications of changes in energy demand due to the variations in climate.

In the case of Macedonia, First and Second National Communications to the United Nations Framework Convention on Climate Change [8,9] have been completed, including inventory of greenhouse gasses (GHG) emissions (developed according to IPCC (Intergovernmental Panel on Climate Change) methodology), mitigation and adaptation studies. The bulk of analytical work has mainly concentrated on measures to mitigate GHG emissions in energy sector [10], as the key contributor to the total GHG emissions. On the other hand, the adaptation studies are mostly of qualitative nature, limited to identification of the potential climate change impacts in a number of sectors, as well as of some options for adapting to these impacts. In very few cases, preliminary estimates of the magnitude of the impacts under several different climate scenarios for some sectors have been presented.

The aim of this study is to find a way of filling in the gaps in climate change research at national level (analytical work and quantitative results related to adaptation), as well as at international level (integrated assessment of mitigation and adaptation in energy sector, analyzing the socio-economic implications of changes in energy demand due to the variations in climate). For this purpose, a methodology for using the national energy model to estimate the effects of climate-driven changes in outdoor air temperatures on space heating and cooling electricity demands of the residential and commercial sectors will be developed and applied. In the next phase estimations will be made about the additional economic costs that these changes imposed on the national electricity and the reduction in costs that could be achieved by targeting investment in new generating capacity through adaptation.

2. Methodology

2.1. Basic model and approach

To simulate the climate change damages and the net benefits of adaptation in the electricity due to changes in outdoor temperatures caused by climate change, the MARKAL model was used.

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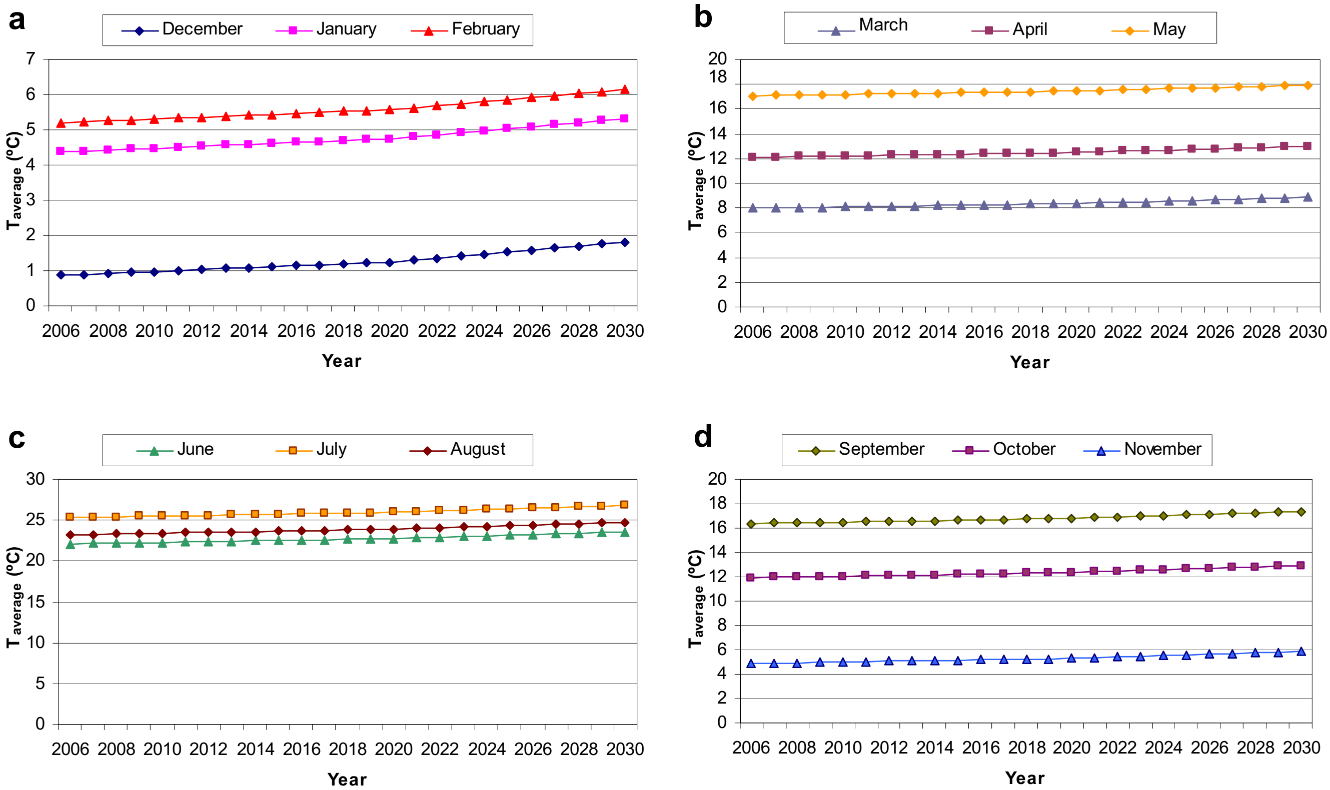

Fig. 1. Projections for the monthly average temperatures. This figure includes four graphs which give projection of monthly average temperatures for four seasons.

The MARKAL model is a dynamic optimization model developed by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA) (ETSAP, 2001) [11]. It depicts both the supply and demand sides of a national or regional power market. It can be used to simulate both the short-run production and consumption of electricity, based on a given mix of electricity generation plants and distribution infrastructure, as well as investment in new generation capacity and distribution infrastructure over time.

The MARKAL modeling framework has existed for 30 years and has been used in over 70 countries and at more than 200 institutions around the world. MARKAL is currently in use for several major international and global applications, and in dozens of developed and developing countries for national strategic planning (see e.g. [12–14]), including analysis of changes in fuel consumption [15], energy saving potential [16] and renewable energy and climate change policies [17–20].

MARKAL analyses not only show what is to be constructed (and also what is not), but also when and for how much [11]. Based on the engineering and economic representations of energy supply, conversion plants and end-use devices in the country – mines, power plants, heat and power facilities, air conditioners, furnaces, light bulbs, etc. – the least cost energy supply and demand balance that can satisfy the physical and policy requirements can be explored by national experts.

A version of this model is currently available for use in Macedonia which was developed in the framework of a regional project[1] to analyze the impact of energy efficiency and renewable policies on the national energy sector [21].

[1] The MARKAL model for Macedonia was developed in the framework of the USAID project "Regional Energy Security and Market Development (RESMD) Strategic Planning".

For this study, the methodological approach involved several steps. The first was to convert the temperature projections developed by Bergant (2006) [22] into changes in heating and cooling degree days over the model horizon. This data will be converted in adjustment factor, which will be used to correct the demand projections in MARKAL model. MARKAL converts this and other information about population and future economic growth into tri-annual demand projections for the residential and commercial electricity demand sectors, over the model's planning horizon, 2009–2030. Unfortunately, the model currently in use in Macedonia does not have the capability to simulate electricity consumption along price-responsive (i.e., downward-sloping) electricity demand functions. And, instead of maximizing the sum of producer and consumer surplus in all of the demand and supply sectors of the national electricity system, it minimizes the net present value of total cost.

However, MARKAL can still be used to shed light on the impacts of climate change on the supply side of Macedonian electricity sector once the projected changes in heating and cooling degree days are calculated. This was done stepwise, as follows:

- Demand projections for the MARKAL model were developed to reflect expected economic development under the current climate (i.e., the Base Case climate);
- The Base Case climate run also was used to determine the optimal generating capacity mix taking into account expected economic development without climate change.
- Three "climate damage" scenarios were developed to reflect different changes in the pattern of seasonal heating and cooling degree days due to climate change;
- MARKAL was run for each of the climate damage scenarios, holding the generation capacities of the various generating resources fixed at levels that were determined in (and, therefore, optimal for) the Base Case climate. This set of runs was

Table 1
Projections for HDD and CDD in Macedonia.

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
HDD1	2538	2533	2528	2523	2518	2513	2508	2503	2498	2493	2488	2483
HDD(average)	2548	2543	2538	2533	2528	2523	2518	2513	2508	2503	2498	2493
HDD2	2566	2561	2556	2551	2546	2541	2536	2531	2525	2520	2515	2510
CDD1	216	221	226	231	236	241	246	251	257	262	267	272
CDD(average)	206	211	216	221	226	231	236	241	246	251	257	262
CDD2	201	206	211	216	220	225	230	235	239	244	249	254
Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
HDD1	2478	2473	2463	2453	2443	2433	2423	2413	2403	2393	2383	2373
HDD(average)	2488	2483	2478	2471	2463	2453	2443	2433	2423	2413	2403	2393
HDD2	2505	2500	2490	2480	2470	2460	2450	2440	2429	2419	2409	2399
CDD1	277	282	291	300	310	319	328	337	346	356	365	374
CDD(average)	267	272	277	283	291	300	310	319	328	337	346	356
CDD2	258	263	272	280	289	298	306	315	323	332	341	349

used to estimate climate change damages, assuming only partial adjustment to climate change;

– MARKAL was run for each of the climate damage scenarios, but was allowed to determine the cost-minimizing capacity mix of generating resources to simulate supply-side adaptation through new investment in generation capacity that was optimal for the expected changes in heating degree days in each of the adaptation scenarios;
– At the end, the economic value of climate change damages was calculated as the differences in total system cost between the climate damage scenarios and the Base Case. The net benefits of adaptation were calculated as the difference in total system cost between the adaptation scenarios and the corresponding damage scenarios.

2.2. Modeling changes in outdoor temperatures due to climate change

Changes in daily air temperatures (min, mean and max) have been projected for Macedonia for the years 2025, 2050, 2075 and 2100 by season [22]. This study was used to forecast the monthly average temperatures over the period 2006–2030, which is the planning period in the MARKAL-model.

Monthly temperature projections are needed to calculate projected heating degree days (HDD) and cooling degree days (CDD) over the planning horizon. The average annual change in temperature was calculated for each period, and projections of the monthly temperatures were developed for each year of the planning period. The four seasonal temperature projections using this data and assumption are shown in Fig. 1.

2.3. Calculation of heating and cooling degree days

The calculations of HDD for this study were made following the methodology used by the District heating company in Macedonia, which was also used in Macedonian MARKAL model. The same approach was used to calculate the CDD values. According to this methodology, the HDD and CDD values for given outdoor temperature are calculated as:

$$HDD = D_{(HS)} \cdot \left(T_{Base} - T_{Av(HS)}\right) \quad (1)$$

$$CDD = D_{(CS)} \cdot \left(T_{Av(CS)} - T_{Base}\right) \quad (2)$$

where:

$D_{(HS)}$ is the number of days in the heating season,
$D_{(CS)}$ is the number of days in the cooling season,
T_{Base} is the base temperature of the space that is heated (in the case of Macedonia is 20 °C),
$T_{Av(HS)}$ is the average temperature during the heating season,
$T_{Av(CS)}$ is the average temperature during the cooling season.

The calculation of the HDD and CDD was made under following assumptions:

– Average duration of heating season – 180 days (from 1 October till 31 March, next year)
– Average duration of the cooling season – 120 days (from 1 June till 31 September)

The projected vales for the HDD and CDD for the average heating and cooling season are given in Table 1, rows HDD1 and CDD1, respectively. In addition, the HDD and CDD were calculated for the heating season duration of 182 days and 112 days for cooling season, rows HDD2 and CDD2 in Table 1, respectively. The HDD(average) and CDD(average) are the mean values.

The next step was to normalize the HDD and CDD adjustments for use in MARKAL. For example, the normalization for HDD1 and CDD1 for 2009 to compute the adjustment factors AdF1 for HDD and CDD is:

AdF1(HDD)(2009) = HDD(1)(2009)/HDD(average)(2009) = 2528/2538 = 0.996, and
AdF1(CDD)(2009) = CDD(1)(2009)/CDD(average)(2009) = 226/216 = 1.047.

Using the projected values from Table 1, four different adjustment factors were calculated, two for HDD and two for CDD, to reflect the climate change damages. The Base Case normalization, by definition, is 1.0. Therefore, if the adjustment factors are less than 1.0 there is a decrease in HDD or CDD and if the adjustment factors are greater than 1.0, there is an increase in HDD or CDD.

Table 2 provides the adjustment factors that are the basis for the climate change damage scenarios.

Table 2
Adjustment factors used in MARKAL model, 2009–2030.

	2009	2012	2015	2018	2021	2024	2027	2030
AdF1(HDD)	0.996	0.996	0.996	0.996	0.994	0.992	0.992	0.992
AdF2(HDD)	1.007	1.007	1.007	1.007	1.005	1.003	1.003	1.003
AdF1(CDD)	1.047	1.044	1.041	1.039	1.050	1.061	1.056	1.052
AdF2(CDD)	0.977	0.975	0.972	0.970	0.980	0.991	0.986	0.982

Table 3
Energy demand projection in commercial and residential sector for the Base Case (ktoe).

Sector	2006	2009	2012	2015	2018	2021	2024	2027	2030	Av.g.r
Commercial	229.8	234.5	254.8	279.1	307.9	334.1	355.0	374.4	395.6	2.3%
Residential	808.6	819.8	854.6	899.4	945.5	1001.5	1058.3	1115.0	1181.6	1.6%

3. Scenarios

The following three sets of scenarios were developed:

– Base Case (BC) – baseline development scenario in which the optimal generation capacity investments are determined, taking into account only country's development plans (without climate change, i.e., the future temperature changes were not taken into account);
– Climate Change Damage Cases (DC) – scenario which introduces the climate changes by adjusting the degree days in accordance with the national climate scenarios, while the generation capacities are fixed to the optimal capacity mix from the Base Case;
– Climate Change Adaptation Cases (AC) – scenario which establishes the optimal capacity mix for adaptation to the climate change by allowing for endogenous capacity adjustments in the model. (The climate changes are the same as in DC, but the method of adjustment to climate change is allowed to differ).

3.1. *Base Case*

The Base Case was developed taking into account all available studies for energy development in the country. As a key document, the Strategy for Energy Development of the Republic of Macedonia until 2030 was considered [23], where the energy resource potential of the country was analyzed in details. All available national data sources (primarily State Statistical Office and national energy balances), as well as some international databases (IEA Databases [24]) were also considered for the key input data in the MARKAL model.

Different types of technologies on the supply side, such as hydro and coal power plants, combined heat and power plants on gas and combined cycle power plants on gas, wind and solar power plants, and various demand devices for space and water heating, cooling and lighting (e.g. heat pumps, solar water heaters) were available for consideration in the model.

Table 3 gives the future energy demands in the commercial and residential sector for the Base Case, based on the projections of GDP and population growth used in MARKAL model.

The average annual growth rate of electricity demand in the commercial sector is about 2.3%. This implies a roughly 72% increase in commercial electricity consumption by 2030. The average annual growth rate for the residential sector is lower, about 1.6%, leading to a 46% increase in residential electricity consumption by 2030. Fig. 2 illustrates how the shares of end-use services change over the planning period, in both sectors for the Base Case for 2006 (inner ring) and 2030 (outer ring).

Over this period, space heating is expected to decrease slightly from around 57% of total electricity demand to 51% in the commercial sector, while space cooling is expected to increase from about 6% of total electricity demand to almost 18%. In the residential sector, space heating is also expected to fall as a share of total electricity demand from almost 65% to about 59%, while the share of space cooling is expected to increase from about 2% of the total to 5%.

The optimal capacity mix for electricity generation that will satisfy the estimated future energy demand in the Base Case is given in Fig. 3. Coal-fired power plants dominate the Base Case for the entire period, followed by the hydro power plants. Coal-fired capacity increases starting in 2021, while hydro capacity increases slowly, pretty much throughout the entire period. Oil fired generation capacity disappears after 2012 (due to retirement), while combined cycle gas and renewable generation grow throughout the period, first replacing the lost oil-fired capacity and then contributing to the general capacity growth of the system.

The total discounted system cost for the Base Case is estimates to be 14,869 million euros.

3.2. *Climate Change Damage Case*

A combination of HDD and CDD adjustment factors were calculated for three alternative climate change damage scenarios using the information in Table 2. These scenarios are defined qualitatively as follows (the quantitative adjustments can be seen in Table 2):

– Damage Case 1 (DC1): Hotter in both Winter and Summer – Decreased demand for heating and increased demand for cooling, using AdF1 for HDD and for CDD;

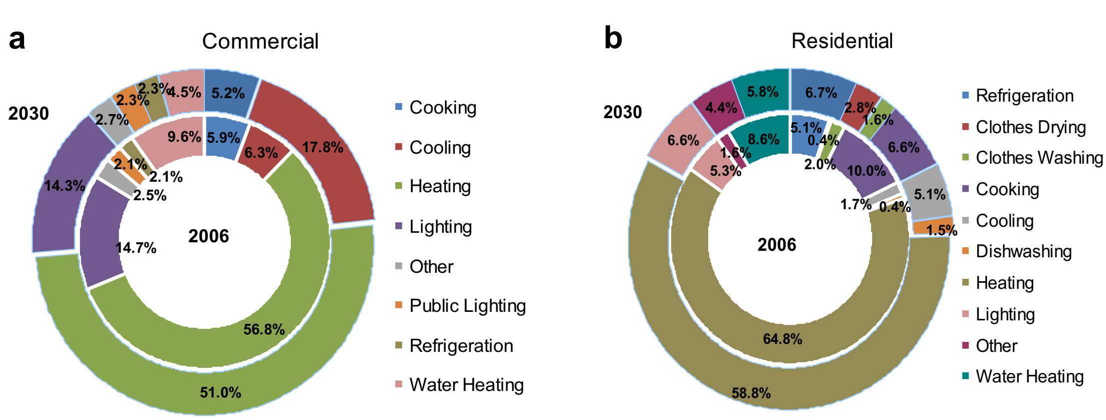

Fig. 2. Shares of end-use services in total energy demand in 2006 and 2030, for commercial and residential sectors – Base Case. This figure illustrates how the shares of end-use services change over the planning period, in commercial and residential sector for the Base Case for 2006 (inner ring) and 2030 (outer ring).

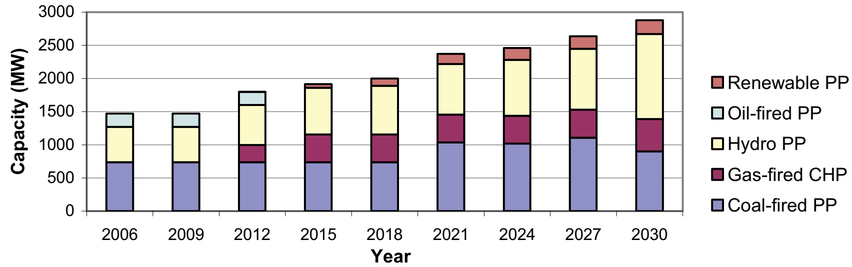

Fig. 3. Electricity generation capacity mix – Base Case. This figure gives the optimal capacity mix for electricity generation that will satisfy the estimated future energy demand in the Base Case.

– Damage Case 2 (DC2): Colder in both Winter and Summer – Increased demand for heating and decreased demand for cooling, using for using AdF2 for HDD and for CDD;
– Damage Case 3 (DC3): Colder in the Winter and Hotter in the Summer – Increased demand for heating and increased demand for cooling, using AdF2 for HDD and AdF1 for CDD.

The optimal generating mix from the Base Case, as previously shown in Fig. 3 was used to constrain the capacity adjustment in the Climate Change Damage Cases in order to simulate partial adjustment to climate change. The resulting changes in residential and commercial heating and cooling demand can be seen in Table 4. The percentage changes are relative to the Base Case. These changes in demand represent the impacts of climate change on residential and commercial energy consumers, allowing them to adjust to climate change on both the supply and demand side using only the technology, policies and know-how in the Base Case. No long-run adaptation is included. As expected, the changes in demand follow the pattern of the simulated changes in heating and cooling degree days (Table 1) and the corresponding adjustment factors introduced into MARKAL (Table 2).

The most interesting feature about Table 4 is that the cooling impacts, both positive and negative, dominate the heating impacts in relation to the Base Case. That is: a change in cooling degree days has a larger impact on the commercial sector than the residential sector. This is "as expected" due to the relative size of the two sectors in terms of their space conditioning use and the fact that space conditioning in the summer is expected to grow more rapidly in the commercial than the residential sector.

The increases in electricity demand due to warmer temperatures in the summer and/or cooler temperatures in the winter are far higher toward the end of the projection period than in the beginning. This is line with the temperature projections and suggests that the MARKAL analysis needs to be extended farther into the future.

Fig. 4 shows the absolute difference in electricity demand for the two sectors in each of the three Climate Change Damage Cases. (These differences will also hold true for the Adaptation Cases since the HDD and CDD are the same for both sets of scenarios in which the climate changes). This figure makes it possible to see that, when hotter summers and winters are expected (DC1) – which is what most Global and Regional Climate Models are predicting for the future – the impact on electricity demand will largely involve increases in commercial sector, and to a lesser extent residential sector, space cooling demand. The DC2 scenario, which simulates colder temperatures-year round does not fit the typical projections of Global and Regional Climate Models, nor Bergant's data [22]. However, it does help us to see that when these conditions occur simultaneously, for example in a single year or for several years in the context of climate variability, that the changes in heating and cooling demands will be virtually offsetting and the net impact very small. DC3, on the other hand, is more realistic since it combines the effects of warmer temperatures in the summer, with colder winters. In portions of Macedonia winter conditions are highly variable. This is a "worst" case, conceptually, since both space heating and cooling demands will increase. Moreover, under these climatic conditions, the relative increase in demand growth is larger in the residential sector than the commercial sector by 2030.

3.3. Climate Change Adaptation Case

The previous section shows the physical and economic damages due to the impact of changes in outdoor temperatures in

Table 4
Percent change (from the Base Case) in residential and commercial electricity demand for the three Climate Change Damage Cases, 2006–2030.

		2009	2012	2015	2018	2021	2024	2027	2030
Hotter in the Summer and in the Winter									
DC1: commercial	Cooling	4.9%	9.9%	13.9%	17.8%	23.3%	30.4%	37.0%	45.0%
	Heating	−0.2%	0.2%	0.7%	0.4%	−1.2%	−1.1%	−2.8%	−4.6%
DC1: residential	Cooling	3.8%	8.8%	13.2%	18.0%	23.7%	30.5%	38.2%	46.3%
	Heating	−0.2%	−0.3%	−0.2%	0.2%	0.2%	−0.4%	−0.1%	−1.8%
DC1: both	DC1 total	0.1%	0.3%	0.9%	1.7%	2.2%	2.7%	3.7%	3.5%
Colder in the Summer and in the Winter									
DC2: commercial	Cooling	−3.3%	−5.8%	−8.2%	−10.5%	−12.3%	−13.3%	−14.4%	−16.6%
	Heating	0.4%	0.8%	0.7%	0.8%	0.0%	0.8%	1.3%	1.1%
DC2: residential	Cooling	−2.5%	−5.0%	−7.5%	−10.6%	−12.5%	−13.3%	−14.4%	−15.9%
	Heating	0.6%	0.9%	1.9%	2.6%	1.9%	2.2%	2.5%	3.2%
DC2: both	DC2 total	0.4%	0.5%	1.0%	1.1%	0.2%	0.3%	0.2%	0.3%
Hotter in the Summer and Colder in the Winter									
DC3: commercial	Cooling	4.9%	9.9%	13.9%	17.8%	23.3%	30.4%	36.9%	42.5%
	Heating	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
DC3: residential	Cooling	4.5%	8.8%	13.2%	18.0%	23.4%	30.3%	37.5%	46.1%
	Heating	0.6%	0.9%	2.0%	2.8%	3.6%	3.7%	3.4%	3.6%
DC3: both	DC3 total	0.7%	1.2%	2.4%	3.5%	4.8%	5.9%	6.8%	8.0%

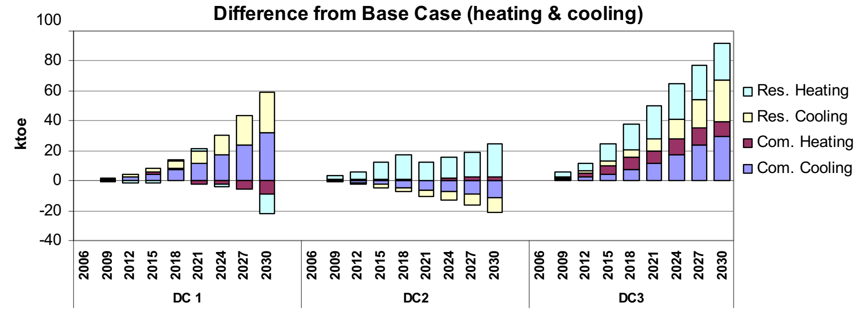

Fig. 4. Difference in the heating and cooling demand for the residential and commercial sectors in the Climate Change Damage Cases compared to the Base Case. This figure shows the absolute difference in electricity demand for the two sectors in each of the three Climate Change Damage Cases (DC1, DC2 and DC3).

Macedonia on space heating and cooling demands for electricity. In estimating these physical and economic impacts, the adjustment of electricity producers was constrained by the generation capacity in the Base Case. This is the same thing as saying the electricity producers remain on their short-run supply curves, as they try to adapt to the increases in electricity demand. However, for the Adaptation Cases, adaptation is treated generally as a process that allows industries and firms to move from their short-run supply curves to the long-run supply curves and invest in new capital and equipment that is optimal for the adjustment to climate change. This process is known as full adjustment. Rather than having to use just the generation capacity they already have at their disposal, they can adjust their generating capacity and distribution capacity so that it is optimal for climate change. As such, an important ingredient of the methodology used in this report is that MARKAL simultaneously selects the long-run cost-minimizing mix of generating plants, their capacities, and operates and maintains the new and old plants consistent with short-run cost-minimization.

The heating and cooling degree days used in the Adaptation Cases are the same ones that were used in the Climate Change Damage (DC1, DC2 and DC3), resulting in the same projection of energy demands (see Table 4). However, to avoid confusion, the scenarios were re-named as follows: Adaptation Case 1 (AC1), Adaptation Case 2 (AC2) and Adaptation Case 3 (AC3).

In this case, the possibility for endogenous adjustment the capacity mix by the model gives the new optimal generation mix, which is different than the generation capacity mix used in the Base and Climate Change Damage scenarios (Fig. 3). The differences in the capacity mix between the three adaptation capacity cases and the Base Case generation capacity are shown in Fig. 5.

The capacity adjustments vary quite a bit in each case. In AC1, virtually no capacity is dropped – only small amounts of renewables between 2024 and 2030 – but modest amounts of combined cycle gas-fired capacity are added (around 38 MW per period) in each period between 2015 and 2030 plus about 15 MW of renewables in 2021. This suggests that, at least in the AC1 case, it will actually be more expensive to adjust capacity to adapt to climate change, relative to the Base Case, than to do nothing. Of course, this is only taking into account the adaptation options that are characterized in the supply side of the MARKAL model and not the demand side. The results for the AC2 case confirm to expectations that adjusting to climate change along their long-run supply curves would make producers better-off (reduce their systems costs, here) than using short-run measures. However, this scenario is the one with the smallest climate change damages. The results for the AC3 scenario, which had the largest climate change damages, look very much like the results for AC1. However, the capacity increases in each of the periods between 2015 and 2027 are greater than in the AC1 case (around 25 MW/period). In both cases, more gas-fired capacity and, in 2021, more renewables capacity is added to cope with climate change.

4. Costs and benefits of adaptation

Climate change benefit and cost measures were estimated in this study to characterize the economic welfare impacts of climate change on the residential and commercial sectors of the national electricity system in Macedonia. These are summarized in Table 5. The estimates of the net benefits of adaptation for two of the three climate change cases were contrary to our expectations for the two most economically "damaging" climate cases AC1 and AC3.

The largest economic losses (climate change damages) were associated with the climate case in which summer temperatures were projected to be the warmest and winter temperatures were

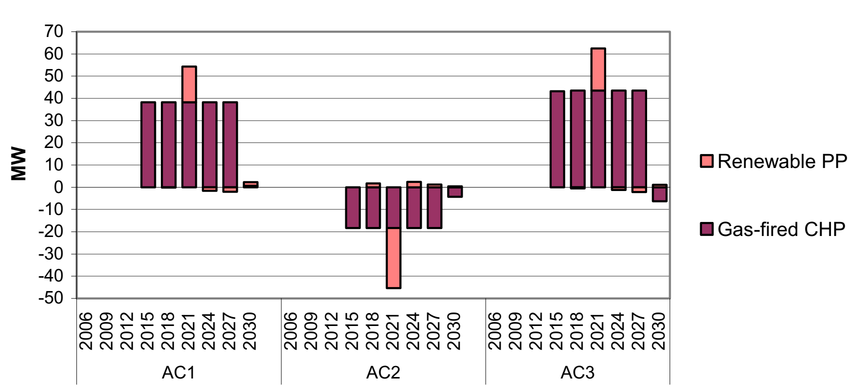

Fig. 5. Difference in the generation capacity mix, ACs vs. BC. This figure shows the differences in the capacity mix between the three Adaptation Cases (AC1, AC2 and AC3) and the Base Case generation capacity.

Table 5
Present value of total system cost for the Adaptation and Damage Cases (million €).

Case/Scenario	System cost adaptation	System cost damage	Climate Change damages	Net benefits of adaptation	Residual damages
Climate Case 1	14,988	14,987	−118	−1	−119
Climate Case 2	14,875	14,877	−8.8	+2	+6.8
Climate Case 3	15,133	15,132	−263.6	−1	−264.6

projected to be the coldest (DC3). This much is common sense. The second largest estimate of climate change damages was associated with the climate case in which it was hotter in both winter and summer (DC1). However, in both of these cases, MARKAL projected that electricity producers would add more capacity and shed very little to adapt to climate change and that this would be more costly. Thus, as shown in Table 5, the net benefits of adaptation were negative, but also very small – around one million euros in both cases. Since the net benefits of adaptation were quite small and the climate change damages were relatively large in these two cases, the value of the residual damages that could not be avoided by climate change were also larger than climate change damages by one million euros. Only the case in which it was projected to be colder in winter and summer (DC2, AC2) showed positive net benefits of adaptation. In this case, climate change damages were an order of magnitude smaller than the other cases, but the benefits of adaptation were twice as large. In percentage terms, shedding capacity in this case along their long-run supply curves reduced climate change damages by about 22%, compared to less than 1% in the other two cases.

5. Conclusions

This study shed important new light on the physical and economic impacts of climate change on the Macedonian electricity generation sector, but it also raised a number of questions about how to use MARKAL to estimate the welfare impacts of climate change and the benefits and costs of adaptation. This was a first attempt and what was learned will be extremely important for preparing future assessments, including the Third National Communication to the UNFCCC and beyond.

The main results could be summarized as follows:

- For the projected changes in temperature, the changes in space heating and cooling demands for electricity were relatively small in the early part of the projection period, but larger for the last ten or so years.
- For the most likely case involving increases in both winter and summer, the increase in summer space cooling demand dominated over the reduction in winter heating demand, and the net increase – though relatively small – grew larger over time.
- The “worst case” in terms of climate change damages involved increases in summer and winter temperatures, as expected.
- Climate change damages, as measured by increases in total system cost, increased with the demand for electricity, over time, but were still relatively small.
- Allowing the electricity supply system to adjust capacity “optimally” to climate change did not always reduce total system costs, which was the opposite of what was expected. In fact, in the two most relevant climate change cases, DC1/AC1 and DC3/AC3, relatively large amounts of capacity were added in the Adaptation Cases to cope with climate change, optimally, over time. Only in AC2 did adaptation reduce the damages in DC2, conforming to expectations.

The biggest question mark in this study is: why the system cost was higher in two of the adaptation cost cases (AC1 and AC3) than in the corresponding Climate Change Damage Cases (DC1 and DC3), given that the climate changes were identical in each “pair” (DC1 with AC1 and DC2 with AC2) and that the system was constrained to operate with the same generating capacity in the Climate Change Damage Cases and the Base Case (but not the Adaptation Cases, where optimal capacity adjustments were allowed).

There are several possible reasons for this:

- The internal cost accounting framework in MARKAL which allowed relatively large amounts of “variable capacity” to satisfy the growing demands in DC1 and DC2, but without changing the system's capital cost, while all of the capacity changes in AC1 and AC2 did involve changes in capital costs, thus changing the system capital costs.
- The fact that the climate change damages were relatively small compared to the total system cost could mean that MARKAL is somewhat insensitive to small shocks.
- The absence of price-sensitive electricity demand functions in MARKAL would make it possible (and even plausible) for the net adaptation benefits in AC1 and AC3 cases to be positive through the effect of increases in the price of electricity on consumer demand that would have differential effects on consumer and producer welfare.

All of these possibilities require further investigation.

Nonetheless, the analysis and the findings presented in this paper are very important, keeping in mind that this is a first attempt in the case of Macedonia (and in the similar countries) and paves the way for future analyses and further improvement of the applied methodology.

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