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# Climate Modeling for Macroeconomic Policy

## A Case Study for Pakistan

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## Abstract

As the effects of climate change become increasingly evident, the design and implementation of climate-aware policies have assumed a more central role in the macroeconomic policy debate. With this has come an increasing recognition of the importance of introducing climate into the economic policy making tools used by central economic policy making agencies (such as ministries of finance and ministries of planning). This paper integrates climate outcomes into a macro-structural model for Pakistan, the kind of model that is suitable for use on a regular basis by ministry staff. The model includes the standard set of variables and economic logic that are necessary for the kinds of forecasting, economic policy, and budgetary planning analysis typically conducted by central ministries. In addition to standard outputs (unemployment, inflation, gross domestic product growth, and fiscal and current accounts), the model generates climate outcomes (tons of carbon emitted and economic and health damages due to higher temperatures and pollution). These outcomes are generated when specific climate policies such as mitigation are analyzed, but also when other policies are analyzed that might have unanticipated climate impacts. The paper describes the changes made to the World Bank's standard macro structural model, MFMod, in integrated climate outcomes, climate policies, and the economic impacts of climate on Pakistan's economy. Notably, carbon-tax scenarios show that a $20 carbon tax can reduce emissions in Pakistan by 36 percent by 2050. Gross domestic product impacts could also be positive, if the revenues from the carbon tax were used to reduce reliance on heavily distorting taxes. The model also quantifies associated co-benefits from reduced local air pollution and better health and productivity outcomes. In the absence of action to restrain climate change, the model suggests that increased temperatures and rain variability could reduce output by as much as 10 percent compared with a scenario where global temperature rises were minimized.

This paper is a product of the Macroeconomics, Trade and Investment Global Practice. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://www.worldbank.org/prwp. The authors may be contacted at aburns@worldbank.org, cjooste@worldbank.org, and gschwerhoff@imf.org.

Produced by the Research Support Team

# Climate Modeling for Macroeconomic Policy: A Case Study for Pakistan[1]

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# 1. Introduction

Avoiding catastrophic climate change by reducing greenhouse gas emissions is a global public good. Left unchecked, climate change will seriously challenge many developing countries. While there is a strong scientific consensus on the threats of climate change and its linkages to economic activity, most developing countries lack the quantitative tools, such as an economic model, to evaluate the economic costs of climate change and the benefits of policies to limit damages. Such a model is needed, if climate change policy and outcomes are to be evaluated on an equal footing with other policy priorities typically addressed by central economic ministries.

The economics of climate change has produced a substantial body of knowledge to date, with the modern literature arguably beginning with the work of William Nordhaus in the late 1970s. Climate economists have illustrated the costs of climate change, in terms of: the increased incidence and seriousness of sudden disasters, the gradual deterioration of production inputs, and the economic costs and benefits of mitigation and adaptation. However, the influence of this work at the individual country level has been limited partly because the scope of analysis has tended to be global, and because much of the analysis has been housed in environment ministries – far from the economic policy-making centers in most economies. And yet, climate change can be expected to generate enormous impacts at the macroeconomic level, in terms of fiscal outcomes, productivity growth, health and economic competitiveness. Furthermore, the linkage between climate change and welfare is much stronger than previously perceived (World Bank 2014), putting climate front and center in policy considerations.

Supported by the *Program for Asia Resilience to Climate Change Trust Fund*, a trust fund of the Government of the United Kingdom,[2] this paper describes how to integrate climate outcomes and policies into the kinds of economic models typically used by non-specialists working in central ministries. As such it is not seen as a replacement for, but a complement to the more detailed models that might be found at an environment ministry or models used in research. The easy-to-use MFMod framework mirrors in many ways the tools already used by central agencies to perform forecasts, budget projections and policy analysis. Integrating the main economic costs and benefits of climate change and climate policy into this easy-to-use framework will help mainstream climate outcomes and policy into the day-to-day work of Ministries of Finance and Economy, putting climate on the same footing as other policy priorities such as unemployment, inflation, fiscal sustainability, and social policies aimed at reducing poverty.

Such an integrated approach should allow climate's effects on the economy to be taken into account more rigorously, but also the effect of economic policy on climate (including policies whose climate effects are indirect and unexpected, such as a tax reform that might benefit a carbon intensive sector of the economy).

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[2] The "Program for Asia Resilience to Climate Change Trust Fund" (PARCC) which aims to increase the resilience of countries in Asia to climate change through regional cooperation, innovation and capacity building. PARCC is supported by the FDCO and the UK Met Office to deliver a transformational change in the quality, accessibility and use of weather and climate information at levels of decision-making to support sustainable development in South Asia.

## 2. Context and background

Despite their significant fiscal and macroeconomic implications, work programs around climate change mitigation and adaptation are poorly integrated into the decision-making process of Pakistan's Ministries of Finance and Planning. In particular, the impacts of climate change are not measured by the macro-fiscal tools used by policy makers in Pakistan. Neither the State Bank of Pakistan (SBP), nor the Ministry of Finance currently uses macroeconomic forecasting and analysis models that capture the potential impact of climate change on the country's economy or of the economy on climate. In large part this reflects the underlying complexity and specialized nature of many climate models, that tend to be housed in Environment Ministries or are run by outside consultants at the request of a Ministry.[3] As a result, policy makers lack the tools necessary to quantify the effect of climate policies (or inaction) on economic growth, fiscal sustainability and Pakistan's broader development agenda.

The work described in this paper addresses this gap by integrating a climate change module into an existing macro-fiscal framework with an easy-to-use interface. The objective is to provide policy makers in Ministries of Finance and Planning with economic models that can be used to plan and analyze the range of economic issues that currently preoccupy them, including fiscal policy (spending and revenues), monetary policy, sectoral activity, external accounts, but which also generate climate outcomes (emissions, economic damages from heat, changed rainfall patterns and pollution) that current tools do not. The model developed maps out the linkages between macroeconomic policy levers, fiscal aggregates and climate outcomes and incorporates a comprehensive set of policy levers covering mitigation measures, co-benefits derived from mitigation, damages caused by climate change and potential adaptation policies.

The work described in this paper focuses on extending an existing macroeconomic modeling framework, which is derived from the World Bank's Macro-fiscal model (MFMod). MFMod is a macrostructural model (see Burns *et al.* (2019) for a technical description) similar to many models used at central banks and ministries of finance around the world. It is the main model used by the World Bank to produce its biannual Macro Poverty Outlook publication.

The model extensions of MFMod for Pakistan (PAKMod) draw from the existing climate literature to introduce emissions and pollution modules; damage functions from higher temperatures, pollution and flooding on economic activity; and an adaptation module to analyze the economic benefits of adaptation investments to adjust to climate change. Importantly, PAKMod recognizes the pervasive informality in the Pakistan economy. Combined with the pre-existing features of the MFMod framework, PAKMod provides a vehicle for systematically evaluating side-by side the climate impacts, as well as the traditional social and economic impacts (growth, fiscal sustainability, inflation and current account stability) of both climate and non-climate policies. While Pakistan is used as a pilot case, many of these climate features can be added to other country models too.

It is expected that the economic modeling techniques developed in this activity will serve as a blueprint for future applications to other countries.

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[3] That current modeling has room for improvement is expressed by Ghafoor *et al.* (2016): "[C]limate-economic models need to be extended to include a wider range of social and economic impacts. Gaps need to be filled, such as the economic responses of developing countries".

## Damages caused by climate change

Climate change is a serious challenge for Pakistan. According to the Global Climate Risk Index 2019, Pakistan was the country 8th most affected in the world by climate-related events between 1998 and 2017, experiencing 145 events over this time period (Kreft et al. 2018).

Pakistan faces three main economic challenges from climate change: increased variability in rain fall leading to water shortages, flooding, and drought; decreased agricultural productivity as temperatures rise; and a decrease in worker productivity as temperatures rise (Young et al. 2019; Asgary, Anjum, and Azimi 2012; Moore and Diaz 2015).[4] Additional types of damages exist, but few data are available (see Section 5).

Agriculture in Pakistan is still the primary source of employment and the primary user of water. Agricultural water use is highly dependent on irrigation in otherwise arid and semi-arid areas through the Indus Basin Irrigation System. Water use in agriculture is inefficient due to the absence of water monitoring and an incomplete water pricing system (World Bank 2018b). With demand from other sectors (municipalities and industry) rapidly growing and current withdrawal levels nearing 60 percent of renewable water supply, misallocation of water resources and resulting supply gaps are already a risk (Young et al. 2019). Climate change is expected to exacerbate this by increasing total water demand by between 16 and 42 percent by 2050 (World Bank, 2019). Water availability is also expected to become more variable, given enhanced glacier melt and more erratic precipitation patterns, which poses risks for the agricultural sector due to limited buffer capacity in the irrigation system.

Agriculture in Pakistan will also be affected as climate change directly impacts land fertility, crop failure rates and livestock productivity.[5] While rising temperatures could lead to minor yield improvements in the north by extending the growing period, the yield of staple crops, such as wheat, maize, or rice, which are predominantly grown in the south, are projected to decrease by up to 20 percent insecurity (compared with a baseline without climate change), resulting in higher food prices and increased food. Livestock production is predicted to decline by 30 percent (relative to baseline), in part because rangelands will become increasingly stressed by longer droughts (UNDP 2017). Salinization of land and aquifers threatens the fertile Indus Delta and sea level rise will aggravate this situation, further contributing to land degradation and loss of fertile soil (Giosan et al. 2014; K. M. Salik et al. 2015).

The third dimension of Pakistan's vulnerability to climate change is exposure to hydrological and meteorological hazards, including storms, floods, heatwaves and droughts. On average, 3 million people are affected by natural catastrophes every year, with floods being the dominant hazard (77 percent of the people affected), followed by droughts (14 percent). The recurring flood events during 2010-14 alone resulted in monetary losses of over US$18 billion (Government of Pakistan 2016). As the cryosphere (snow and ice cover) in the mountainous areas is retreating and sea levels are rising due to climate change, the risk of flooding is increasing. Other extreme events which are likely to become more prevalent include heatwaves and droughts. For instance, the unprecedented 2015 heatwave in Karachi took the lives of over 1,200 people (MOCC Pakistan 2015).

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[4] Other challenges related to climate change include coastal erosion (Kanwal et al. 2020), and forest management (World Bank 2018a). These are not modeled in this paper.

[5] For a review of climate change impacts on agriculture, see (UNDP 2017; World Bank 2016).

## Policy options to address climate change

Policy options to address climate change can take one of two forms:

**Mitigation policies** seek to reduce Pakistan's contribution to global and local climate change. Although Pakistan – according to the Carbon Dioxide Information Analysis Center – only contributed around 0.46 percent of global carbon emissions in 2014, mitigation policies that seek to reduce emissions or limit their rise as the economy grows are relevant because of Pakistan's high emission intensity of GDP. Unless emissions intensity declines more quickly than in the past, Pakistan's emissions are expected to more than double by 2080 as the country develops.[6] While reduced contribution global emissions are a clear benefit, albeit small, mitigation measures can also generate important co-benefits that support the economy.

**Adaptation policies** can help reduce Pakistan's vulnerability to climate change shocks. Adaptation includes all policies that reduce the economic and social impact of climate degradation. While adaptation is often beneficial at the individual level, meaning that the private benefits will exceed the cost of adaptation, there are many cases in which externalities or market failures imply that private individuals will not undertake the investment, even though at the social level the benefits of adaptation (private and social) would exceed the costs. For example, economies of scale mean that the benefits from a single dyke around a community might exceed the costs of its production and might be much less expensive than many private dykes.

## Existing climate mitigation policy in Pakistan

The energy sector represents 46 percent of emissions in Pakistan with agricultural emissions (principally from livestock) reflecting a substantial 41[7] percent share (Sánchez-Triana et al. 2014; World Bank 2018b). Energy is the fastest growing contributor to GHG emissions, with increasing demand for energy being met primarily through imported natural gas and oil, with some contribution from hydropower (Figure 1).

Three factors drive the negative climate implications of the energy sector. First, Pakistan's energy mix directly exacerbates GHG emissions, as natural gas losses during transport are high[8] and natural gas releases methane, which, when it is leaked, traps 28-34 times more heat in the atmosphere than an equivalent amount of carbon. Second, significant subsidies result in lower domestic market prices for natural gas than international market prices, thus increasing demand. Third, the non-hydroelectrical portion of Pakistan's power sector is characterized by a dominance of comparatively inefficient public power plants, whose operational performance is further constrained by underpriced electricity and high transmission and distribution losses. The lack of access to reliable electricity for households and firms imposes significant economic costs, as firms and individuals are forced to rely on inefficient and high-emission private generators which contributes to reduce household and firm productivity. Estimates put these costs at around 4.75 percent of GDP (Zhang, 2018).

Reducing emissions requires policy measures that internalize environmental externalities in gas and oil consumption, reduce gas leakage, limit theft of electricity and promote renewable energy use. Under the Paris Agreement Pakistan has highlighted its intention to reduce GHG emissions by 20 percent by 2030, relative to the projected emissions. Prioritized future mitigation pathways to achieve this target include,

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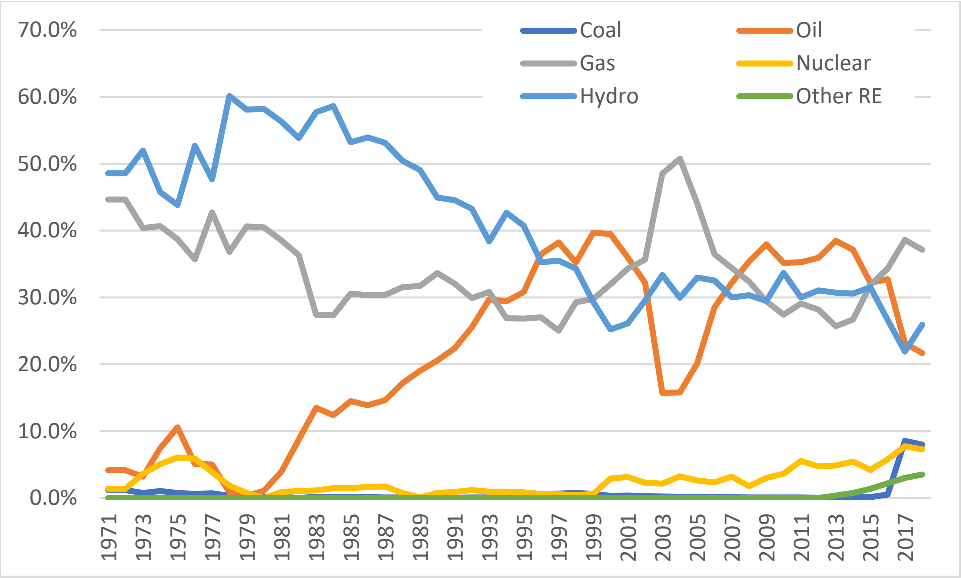
[6] After India, Pakistan produces more GHG emissions per GDP than any other country in the region.

[7] https://www.climatelinks.org/sites/default/files/asset/document/GHG%20Emissions%20Fact%20Sheet%20Pakistan_6-3-2016_edited_rev%2008-18-2016.pdf

[8] Natural gas losses peaked at 14.3 percent in 2015 – compared to 1 to 2 percent in OECD countries.

among others, increasing energy grid efficiency, coal generation efficiency and renewable and hydro energy expansion. In addition, Pakistan levies various taxes on fuel – including petrol and gas levies, customs duties on import and sales tax - which have the potential to provide a disincentive for burning fossil fuels. However, according to IMF (2018), there was a gap of USD 18.56bn (6.82 percent of GDP) between the fuel taxes justified by global external costs and the fuel taxes that Pakistan actually levies (only USD 4.8 billion is the global warming externality, the rest are domestic externalities). Most of this tax gap comes from low oil prices (8.41bn), followed by natural gas (5.55bn), coal (1.94bn) and electricity (2.57bn).

Figure 1: Electricity generation by source in Pakistan



Source: (IEA 2021)

## Existing efforts to adapt to climate change in Pakistan

The extent of Pakistan's vulnerability to climate change induced disasters emphasizes the need for adaptation measures, which are guided by the National Disaster Risk Reduction Policy (2013). The policy advocates creating resilient communities with disaster risk reduction interventions at the local level, including the need to build links, information exchange and communication channels between community-based actors, local governments, and District Disasters Management Authorities/Provincial Management Authorities. The Government of Pakistan has also recently passed the Climate Change Act 2017, which establishes the Climate Change Authority and Climate Change Fund to advance the climate change agenda, tasked with contributing toward prevention and mitigation of disaster and climate risks.

## Future mitigation and adaptation options in Pakistan

Going forward, multiple pathways exist for Pakistan to increase its mitigation and adaptation efforts. As concerns mitigation. For one, fuel taxation that equalizes the marginal cost paid by fuel consumers with the internal and external costs generated by burning fuels can play a central role in reducing emissions while generating positive fiscal co-benefits. Currently hydroelectricity, is the dominant source of renewable energy production (Figure 2). However, going forward while there is scope for expansion of hydro power, the bulk of new renewables are destined to come from solar (Table 1 see (Ghafoor et al. 2016)).

Figure 2: Electricity capacity from renewable energy in Pakistan

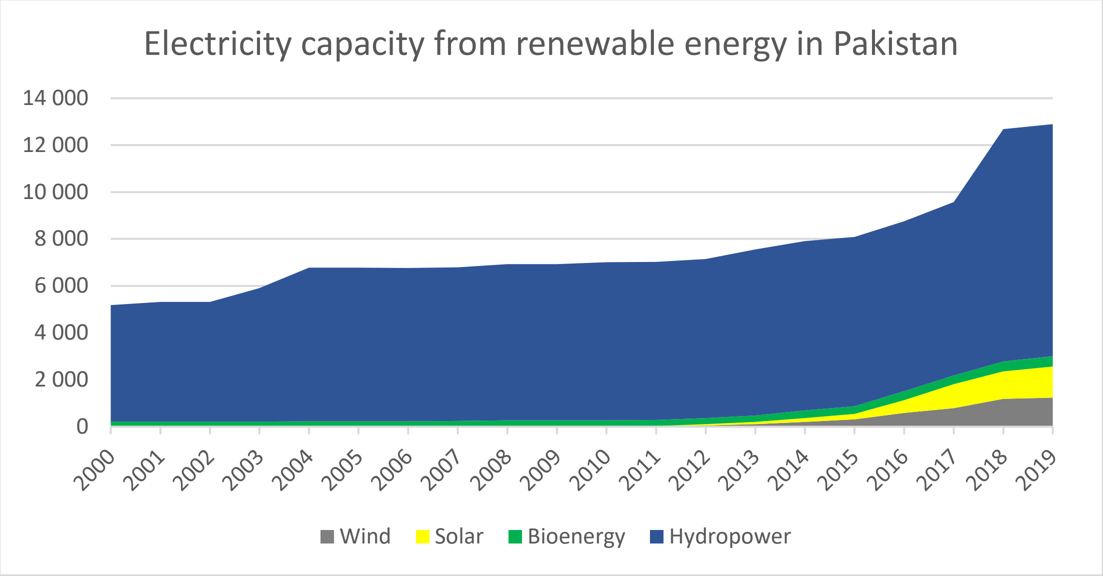


*Table 1: Capacity and potential for renewable electricity in Pakistan, in MW*

| Source | Capacity in 2019 | Potential according to Ghafoor et al. (2016) |
|---|---|---|
| Hydropower | 9,900 | 45,000 |
| Solar | 1,329 | 2.9 Million |
| Bioenergy | 432 | 1,012 |
| Wind | 1,236 | 20,000 |

With regards to future adaptation measures, evidence highlights the major potential benefits of developing more productive crops, extending agricultural research and extension, improving irrigation efficiency and encouraging the use of rainfall index insurance (Parry et al. 2014a; Parry, Mylonas, and Vernon 2018). Reducing the economic impact of potential future climate-related disasters (floods, droughts, heat waves) requires investment in the resilience of infrastructure and the development of a robust disaster risk management (Stéphane Hallegatte, Hourcade, and Dumas 2007). For instance, improving hydromet infrastructure (local weather, notably rainfall, forecasting and dissemination) and operationally targeted climate information and early warning systems can help key economic sectors such as agriculture, aviation, water, urban infrastructure, hydropower, and tourism adapt to and overcome climate-induced vulnerabilities.

## 2.1 Link to other World Bank Projects

The model described in this paper has the potential to inform and support other climate-related work in Pakistan. Recently, the World Bank Islamabad office Pakistan CMU has begun work on a climate change platform to consolidate all climate-related analytical work in Pakistan to extract and disseminate key lessons for policy makers and to streamline their application into project preparation. The model can help develop an integrated approach and assessment of the broader economic effects associated with these efforts. At a regional level, the model can support the planned technical assistance project ("Regional Climate Resilience and Adaptation Program") aimed at informing national-level investments and programs on climate resilience across South Asia. At the same time, this model will provide a convenient platform for monitoring the climate co-benefits of seemingly un-related policies, such as tax and spending policies that may have important indirect climate impacts.

In addition to the climate change platform and regional work, the proposed model can also support the ongoing dialogue with the Government of Pakistan relating to climate change at the federal and provincial level. This includes the provision of technical assistance to achieve Pakistan's INDCs under the "Green Growth and Climate Resilient Development" project and a continuous dialogue with the Ministry of Climate Change centered around the impact of climate change on water security and agricultural productivity. Finally, the models will also allow for analysis and simulation of policy options outside the direct realm of climate change, such as the fiscal and economic effects of tax policy changes.

## 3. Introducing climate considerations into PAKMod

PAKMod is a macrostructural model, with the long run determined by a mixture of calibrated and estimated parameters following a neoclassical framework. The short run is primarily data driven. External and domestic shocks perturb the economy away from equilibrium, with the speed that the economy returns to equilibrium determined econometrically on the basis of the way the economy has adjusted historically. The functional forms of the equations in the model are derived from economic theory where household tend to optimize consumption decisions to maximize utility, and firms minimize costs by adjusting their use of factor inputs. The model is not, however, fully micro-consistent in the way that CGE or DSGE models are. The main strand of climate-macro models can be summarized as:

- **Integrated Assessment Models (IAMS**): Integrated Assessment Models (IAMs) are large-scale numerical models, which combine an economic analysis with key insights on climate impacts and climate policy. Typically, the models (i) take a global and mitigation perspective, (ii) consider long time horizons of 30 to 100 years into the future and (ii) have a major focus on the energy system.
- **Spreadsheet models:** The IMF has developed a model in an Excel workbook (Parry et al. 2014b; Parry, Mylonas, and Vernon 2018) to evaluate climate policy. The workbook contains large amounts of data on greenhouse gas emissions and a number of co-benefits, including for developing countries. It allows a fast and comprehensive evaluation of the quantitative effects of policies related to climate change. It has been applied to guide G20 countries in terms of actions that will help them converge to their GHG pledges. In general, the framework underscores the efficiency of pricing instruments (e.g., carbon tax) as opposed to other instruments (e.g. energy efficiency systems and fuel taxes) to hit the climate targets. The CPAT (carbon pricing and taxation) model under development by the World Bank and the IMF covers similar ground but also includes pollution, health and productivity effects from GHG production. The framework accounts for the energy system and models the impact of carbon prices on stranded assets too.
- **DSGE models:** Some DSGE models include fossil fuels directly as an input into production and consumption (Hassler and Krusell, 2018). These models include features from the climate economics literature such as a carbon-cycle component in which emissions lead to greenhouse gasses which warms the earth's atmosphere. The loop is closed via a damage function that relates GDP losses to the amount of carbon in excess of some defined steady state. Damages in these models can either be simulated via changes in TFP or changes in utility. Typically, these models are assumed to return to the steady state growth rate – i.e. damages affect levels but not growth. These models exclude significant nonlinearities or tipping points where economies are structurally altered. That said, nothing hinders the inclusion of tipping points. Lemoine and Traeger (2014) shows that tipping points raises the optimal carbon tax, with the resulting policy aiming to lower optimal peak warming by 0.5 degrees centigrade. With extreme climate shocks, rebuilding can be delayed, generating hysteretic effects that can alter the steady state (Stéphane Hallegatte, Hourcade, and Dumas 2007).
- **Macro Structural Models:** Macro structural models are the mainstay forecasting and policy tools in many central banks and ministries of finance (Dalsgaard, André, and Richardson 2001; Brayton, Laubach, and Reifschneider 2014; Saxegaard 2017). Like computable general equilibrium (CGE) and DSGE models, these are general equilibrium models that cover the entire

macro economy by linking various accounts through a set of identities and behavioral equations. There are relatively few examples of macro structural models being used for climate change policy. Notable exception include the Cambridge Econometric Energy-Environment-Economy model (Cambridge Econometrics 2014), the St. Lucia model of the World Bank and the IMF model described in Parry, Mylonas and Vernon, (2018).

- **Stock-flow Consistent Models:** These models are based on the interactions of the balance sheets of the private sector (banking and non-bank), household, government, external sector and monetary policy sectors. A key difference in these models and other models is that firms and households do not necessarily maximize a utility or profit function (see for example Monasterolo and Raberto (2018). The models have strong Keynesian effects and focus on disequilibrium behavior of firms and households. It is not always possible to model the balance sheet of all the economic actors since data are not readily available for data poor countries. The climate modules in these models are very similar to a DSGE or MS model.
- **Recursive Dynamic Computable General Equilibrium Models (DR-CGE):** Dynamic Recursive CGE models describe the behavior of economic agents with a system of equations. The economic behavior in DR-CGE models is very tightly linked to standard economic theory. Generally, these models assume that all markets in the analyzed economy are in equilibrium (i.e., observed relative prices clear all markets simultaneously), and implicitly that the observed state of the economy reflects a constrained optimum. These were among the first models to be used to analyze a more granular level than the IAMS the impacts of climate change on economies and of economic policy on climate.

Given data constraints in some equations, several parameters were calibrated using the methodology outlined in Burns and Jooste (2019). Beyond customizations necessary to better capture the structure of the Pakistani economy, five significant features were added to the framework:

1. **A more disaggregated energy sector** was integrated into both the production and consumption sides given the importance of hydrocarbons as a source of greenhouse gas emissions and particulate pollution.
2. **An emissions and pollution module** were added to capture the main channels by which economic activity affects climate outcomes.
3. **Damage functions** were introduced to capture how pollution, flooding and higher temperatures impact economic activity by reducing working time; by reducing labor productivity; and by reducing agricultural productivity.
4. **Adaptation investment functions** were introduced to capture how investments to increase the climate resilience of the economy can reduce the damages that might otherwise occur.
5. **An informal sector** was introduced to ensure that economic behaviors unique to that part of the economy were properly captured by the model.

The following sub-sections describe the adjustments made to the standard MFMod structure to accommodate climate change in PAKMod.

## 3.1 GDP components

As in MFMod, the modeling of GDP comprises three measurements. GDP from the (i) expenditure side, (ii) production side and (iii) income side. Each of these are described below.

### 3.1.1 GDP: Expenditure measure

GDP at market prices $(Y_t)$ can be measured in nominal and real terms (denoted with superscript $CN$ and $KN$, respectively), while the deflator has superscript $XN$. Market price GDP is then the sum of household consumption $\left(C_t^j\right)$, government consumption $\left(CG_t^j\right)$, investment $\left(I_t^j\right)$, which is the sum of private and public investment $\left(IP_t^j + IG_t^j\right)$, exports $\left(X_t^j\right)$, less imports $\left(M_t^j\right)$, change in inventories $\left(II_t^j\right)$ and a statistical discrepancy $\left(Stat_t^j\right)$ for $j = CN, KN$ and for all time periods $t$:

$$Y_t^j = C_t^j + CG_t^j + I_t^j + X_t^j - M_t^j + II_t^j + Stat_t^j$$

Historic deflators are calculated as the nominal variables divided by real variables.

The modeling equations for each component are described below.

### 3.1.2 Household Consumption

#### *3.1.2.1 Real household consumption*

In the long run, aggregate consumption $(C_t^{KN})$ is determined as the solution to a representative household's intertemporal utility maximization problem. The split of consumption into energy and other consumption is obtained from a CES aggregator:

The household maximizes utility (positive in consumption and leisure):

$$\sum_{i=0}^{\infty} \beta^i \left( \frac{C^{KN}{}_{t+i}^{1-\sigma}}{1-\sigma} - \frac{N_{t+i}^{1+\phi}}{1+\phi} \right)$$

With the following Lagrangian:

$$\sum_{i=0}^{\infty} \lambda_{t+i} \left[ (1-\tau_t^N) W_t^{CN} N_t - (1+\tau_t^C) P_{t-1}^{C,XN} \left( \int_0^1 C_{j,t}^{KN\frac{\gamma-1}{\gamma}}\, dj \right)^{\frac{1}{\gamma-1}} - R_{t+i} D_{t+i} + D_t \right]$$

where $N_t$ is labor supply, $W_t$ is the household wage, $R_{t+i}$ is the interest on borrowing, $D_t$ is current period borrowing and $\sigma$ is the elasticity of substitution, $\phi$ is the inverse Frisch elasticity and $\lambda_{t+i}$ is the Lagrange multiplier.

Note that $\left( \int_0^1 C_{j,t}^{KN\frac{\gamma-1}{\gamma}}\, dj \right)^{\frac{1}{\gamma-1}} = C_t^{KN}$ where we have substitution over energy and non-energy goods.

The first order conditions yield the labor supply equation and the Euler equation for consumption. It also yields the derived demand for energy and non-energy consumption by households as a function of the associated price indices.

In the long-run, household consumption grows in line with real disposable income $YD_t^{CN}$, which equals nominal wage earnings $(W_t)$ on labor $(N_t)$ net of taxes $(\tau_t^{DRCT})$, deflated by the household consumption deflator $\left(P_t^{C,XN}\right)$. It also includes nominal transfers from the government to households $(G_t^{SOC})$. Disposable income also includes net remittances – remittance inflows less remittance outflows $(XREMT_t^{CD} - MREMT_t^{CD})$ – recorded in US dollars $(CD)$ and converted into local currency by with the exchange rate $\left(FX_t^{PK,US}\right)$. Disposable income is thus given as

$$YD_t^{CN} = W_t N_t (1 - \tau^{DRCT}) + G_t^{SOC} + (XREMT_t^{CD} - MREMT_t^{CD}) FX_t^{PK,US}.$$

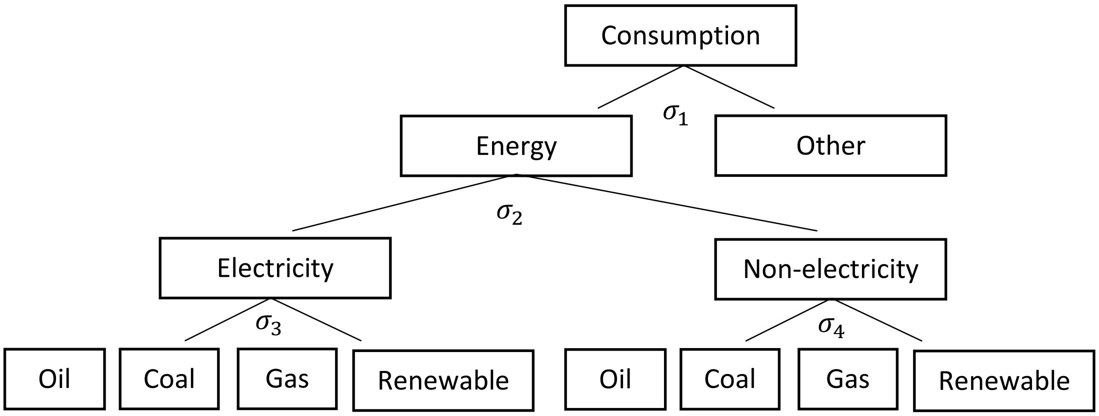
In the steady state consumption is a fixed share of GDP, since with stable tax rates, the wage bill grows in line with potential GDP. Disposable income also enters the short-run part of the equation. The real interest rate (proxied as the average interest of debt), enters the household's decision with a negative coefficient:[9]

$$\Delta \ln(C_t^{KN}) = \alpha + \theta \left[ \ln(C_{t-1}^{KN}) - \gamma^C \ln\left(\frac{YD_{t-1}^{CN}}{P_{t-1}^{C,XN}}\right) \right] + \beta_1 (i_t^B - \pi_t) + \beta_2 \Delta \ln\left(\frac{YD_t^{CN}}{P_t^{C,XN}}\right) + \varepsilon_t^C$$

where $\Delta$ is the difference operator, and $\varepsilon_t^C \sim IID$ is a residual.

The parameter $\theta$ is an estimate of the speed of adjustment towards equilibrium (pinned down by real disposable income), while $\gamma^C$ is the long-run elasticity (calibrated to equal 1) of consumption with respect to permanent income. $\beta_1 < 0$ indicates that an increase in the short-term interest rate reduces consumption in the same period. $\beta_2$ measures how current income influences consumption in the same period. Note that lower case letters here, and in the rest of the paper, denotes variables in logs.

Total consumption is split into a composite energy good and a composite non-energy good, using a nested constant elasticity of substitution framework. This provides three nests for consumption: (i) the split of consumption into energy and non-energy, (ii) the split of energy into electricity and non-electricity and (iii) the split of electricity and non-electricity into specific energy sources (oil, coal, natural gas, and renewables). Since energy sources are imperfect substitutes, we can either model consumption as an almost ideal demand system or as a constant elasticity of substitution (CES) framework. We follow the latter.



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[9] The relationship between this equation and the Euler equation can be illustrated in a two-period problem. Start with $C_2^{KN} = C_1^{KN} \beta (1+r)^{\sigma}$. If we substitute this into a budget constraint $C_1^{KN} + \frac{C_2^{KN}}{1+r} = W_1 N_1 (1 - \tau_1^N) + \frac{W_2 N_2 (1 - \tau_2^N)}{1+r}$ we obtain $C_1^{KN} = \frac{W_1 N_1 (1-\tau_1^N) + \frac{W_2 N_2 (1-\tau_2^N)}{1+r}}{1+\beta(1+r)^{\sigma}}$. Divide and multiply by $W_1 N_1 (1 - \tau_1^N)$: $C_1^{KN} = \kappa W_1 N_1 (1 - \tau_1^N) \left( 1 + \frac{\frac{W_2 N_2 (1-\tau_2^N)}{W_1 N_1 (1-\tau_1^N)}}{1+r} \right)$. In the steady state the real wage bill grows in line with long-term GDP: $\frac{W_2 N_2 (1-\tau_2^N)}{W_1 N_1 (1-\tau_1^N)} = 1 + \Delta y_t^*$ where the constant $\kappa = \frac{1}{1+\beta(1+r)^{\sigma}}$. The consumption equation becomes $C_1^{KN} = \kappa W_1 N_1 (1 - \tau_1^N) \left(1 + \frac{1+\Delta y_t^*}{1+r}\right)$, or in logs: $\ln(C_t^{KN}) \approx \ln(\kappa) + \ln\big(W_1 N_1 (1 - \tau_1^N)\big) + \Delta y_t^* - r_t$, which corresponds to the long-run part of the consumption equation above.

The first nest is between energy and non-energy consumption:

$$(C_t^{KN})^{\frac{\sigma_1-1}{\sigma_1}} = \omega_E^{Con}\left(C_{E,t}^{KN}\right)^{\frac{\sigma_1-1}{\sigma_1}} + \left(1-\omega_E^{Con}\right)\left(C_{Oth,t}^{KN}\right)^{\frac{\sigma_1-1}{\sigma_1}}$$

With the following first-order conditions:

$$C_{E,t}^{KN} = \left(\omega_E^{Con}\right)^{\sigma_1}\left(\frac{P_t^{C,XN}}{P_{E,t}^{C,XN}}\right)^{\sigma_1} C_t^{KN}$$

$$C_{Oth,t}^{KN} = \left(\omega_{Oth}^{Con}\right)^{\sigma_1}\left(\frac{P_{T,t}^{C,XN}}{P_{Oth,t}^{C,XN}}\right)^{\sigma_1} C_t^{KN}$$

The corresponding variables in current values are simply

$$C_{E,t}^{CN} = P_{E,t}^{C,XN} * C_{E,t}^{KN}$$

$$C_{Oth,t}^{CN} = P_{Oth,t}^{C,XN} * C_{Oth,t}^{KN}$$

Next, electricity and non-electricity is derived from total energy consumed. The first order conditions are:

$$C_{Elec,t}^{KN} = \beta_{Elec}^{\sigma_2}\left(\frac{P_{E,t}^{C,XN}}{P_{Elec,t}^{C,XN}}\right)^{\sigma_2} C_{E,t}^{KN}$$

$$C_{OE,t}^{KN} = \beta_{OE}^{\sigma_2}\left(\frac{P_{E,t}^{C,XN}}{P_{E,t}^{C,XN}}\right)^{\sigma_2} C_{E,t}^{KN}$$

With energy prices being an aggregate of electricity and other energy prices:

$$P_{E,t}^{C,XN} = \left[\beta_{Elec}^{\sigma_2} {P_{Elec,t}^{C,XN}}^{1-\sigma_2} + \beta_{OE}^{\sigma_2} {P_{OE,t}^{C,XN}}^{1-\sigma_2}\right]^{\frac{1}{1-\sigma}}$$

The CES nest is completed by writing out the consumption of each commodity type. Optimal consumption is:

$$C_{Elec,k,t}^{KN} = a_{1k}^{\sigma_3}\left(\frac{P_{Elec,t}^{C,XN}}{P_{Elec,k,t}^{C,XN}}\right)^{\sigma_3} C_{Elec,t}^{KN}$$

$$C_{OE,k,t}^{KN} = a_{2k}^{\sigma_4}\left(\frac{P_{OE,t}^{C,XN}}{P_{OE,k,t}^{C,XN}}\right)^{\sigma_4} C_{OE,t}^{KN}$$

Total prices for electricity and other energy are:

$$P_{Elec,t}^{C,XN} = \left[\sum_k a_{1k}^{\sigma_3} {P_{Elec,k,t}^{C,XN}}^{1-\sigma_3}\right]^{\frac{1}{1-\sigma_3}}$$

$$P_{OE,t}^{C,XN} = \left[\sum_k a_{2k}^{\sigma_4} P_{OE,k,t}^{C,XN\ 1-\sigma_4}\right]^{\frac{1}{1-\sigma_4}}$$

#### 3.1.2.2 The consumption deflator

The consumption deflator is given by a CES aggregation scheme of energy prices ($P_{E,t}^{C,XN}$) and non-energy prices ($P_{Oth,t}^{C,XN}$), with an elasticity of substitution of 1.2.

$$\left(P_t^{C,XN}\right)^{1-\sigma_1} = \left(\omega_E^{Con}\right)^{\sigma_1}\left(P_{E,t}^{C,XN}\right)^{1-\sigma_1} + \left(1-\left(\omega_E^{Con}\right)^{\sigma_1}\right)\left(P_{Oth,t}^{C,XN}\right)^{1-\sigma_1}$$

The disaggregated commodity prices in the model are exogenous and expressed in local currency terms and adjusted for taxes/subsidies. The aggregation of energy-related commodity prices (using a CES assumption) leads to the energy price index.

The non-energy household price deflator then follows Burns et al. (2019) and is represented as:

$$\Delta p_{Oth,t}^{C,XN} = \alpha \Delta p_{Oth,t-1}^{C,XN} + (1-\alpha)\left(\vartheta \Delta p_t^M + (1-\vartheta)\Delta p_t^{fcst}\right) + \Delta\tau_t^{VAT} + \varepsilon_t^{OTH}$$

where $\alpha$ measures the degree of price stickiness, $\Delta p_t^M$ is import price inflation, $\Delta p_t^{fcst}$ is producer price inflation, $\tau_t^{VAT}$ is the effective VAT rate and $\vartheta$ is the estimated weight of imports in the consumption basket.

#### 3.1.2.3 Nominal government consumption

Nominal consumption is determined by the product of the deflator and real consumption, measured at constant prices:

$$C_t^{CN} = C_t^{KN} P_t^{C,XN}$$

### 3.1.3 Government Consumption

#### 3.1.3.1 Nominal government consumption

Data for government consumption in the national accounts, although measuring the same economic phenomenon and both reported in nominal terms, are different from data for government consumption recorded in the government finance statistics accounts (GFS. Differences arise from different accounting methodologies (accrual versus cash basis), slightly different definitions of categories and measurement error. The GFS accounts provide estimates for the use of nominal goods and services ($G_t^{GS}$) and the government wage bill ($G_t^{COE}$). In the model, the sum of the two proxies is nominal government consumption in the national accounts ($CG_t^{CN}$). The equation below maps the fiscal accounts to the national accounts via a growth equation where $DUMH$ is a dummy that is equal to 1 in-sample and 0 in the forecast period. As written, the equation, called a *quasi-identity* by the World Bank modeling team, ensures that the historical discrepancy between the accounts is retained, but that in the projection period the two concepts, which seek to measure the same phenomenon but have different levels historically, grow at the same rate:

$$\Delta \ln(CG_t^{CN}) = \Delta \ln(G_t^{GS} + G_t^{COE}) + \beta DUMH + \varepsilon_t^{G}$$

#### 3.1.3.2 Government consumption deflator

Following Burns et al. (2019), the deflator for government consumption is indexed to the household deflator:

$$\Delta p_t^{G,XN} = \alpha + \theta\left[p_{t-1}^{G,XN} - p_{t-1}^{C,XN}\right] + \beta \Delta p_{t-1}^{G,XN} + (1-\beta)\Delta p_t^{C,XN} + \varepsilon_t^{PG}$$

This equation setup ensures that in the long run government prices grow at the same rate as inflation – implying stable relative prices.

#### 3.1.3.3 Real government consumption

Real government consumption is then an identity equal to nominal consumption divided by the NIA government consumption deflator:

$$CG_t^{KN} = \frac{CG_t^{CN}}{P_t^{G,XN}}$$

### 3.1.4 Investment

#### 3.1.4.1 Real private investment

Private investment decisions depend on (i) adjustment costs; (ii) long-run returns and (iii) short-run returns vs. short-run costs. The framework is based on Tobin's Q, where the Q ratio is the solution to the return to capital and the cost of capital (or market value of assets) of its replacement value. In this model, Tobin's Q is defined as the ratio of the marginal product of capital to the real cost of capital. The long run solves for the steady state investment-capital ratio, which equals potential GDP growth plus the rate of capital depreciation.

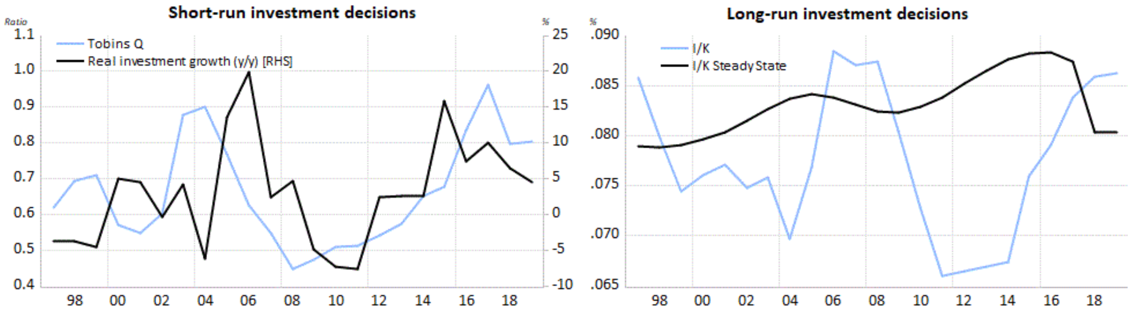
The investment equation can be expressed as:

$$\frac{{I_t^{KN}}^{P}}{K_{t-1}} = \beta_1 + \beta_2 \ln\left(\frac{\frac{D_t^e}{K_t}}{r_t^B + \epsilon}\right) + (1-\beta_3)(\Delta y_t^* + \delta) + \beta_3 \frac{{I_{t-1}^{KN}}^{P}}{K_{t-2}} + \varepsilon_t^{IP}$$

In the long-run Tobin's Q $\left(\frac{\frac{D_t^e}{K_t}}{r_t^B+\epsilon}\right)$ equals 1 (and hence drops out of the equation), which implies that the investment-capital ratio solves to the steady state $(\Delta y_t^* + \delta)$. The speed of adjustment to the long run depends on $\beta_3$ , which measures the degree of investment persistence.

Figure 3 compares the short and long-run components to investment. Real investment growth seems to track our measure of the Tobin's Q relatively well. The steady state investment to capital ratio varies between 8% and 8.5% over the historical sample period.

Figure 3: Determinants of investment for Pakistan



Source: Macro Poverty Outlook and own calculations

### 3.1.4.2 Nominal government investment

Nominal government investment in the national accounts are modeled to follow nominal capital expenditure in the government finance statistics (GFS). The investment concept from the GFS used is net acquisition of non-financial assets $(G_t^I)$. Total government spending on investment includes both investment in productive capital and adaptation investments that do not add to the productive capital stock, but make the economy more resilient to climate events (both those that destroy productive capital such as floods or destructive winds and those that make the economy more resilient to the damaging effects (lower productivity) of higher temperatures).

Total government investment is therefore given as $IG_t^{CN} = I_t^{GP,CN} + I_t^{A,CN}$ where $I^A$ refers to adaptation investment and $I^{PG}$ to productive investment. Historically, separate data for adaptation investment do not exist but are subsumed into the total of government productive investment (implying zero reported adaptation investments and zero reported adaptation capital). To the extent that such investments were undertaken then $I^{GP}$ (and the productive capital stock upon which it depends) are over-estimated.[10]

The link between the national accounts and GFS data follows a quasi-identity that preserves historical data but ensures that in the forecast period the two notions grow at the same pace:

$$\Delta\ln(IGP_t^{CN}) = \Delta\ln(G_t^I) + \beta DUMH + \varepsilon_t^{IG}$$

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[10] The modeling distinguishes between private-sector adaptation and public sector adaptation. As climate change occurs and certain types of crops become productive, but others improve (or fall by less) producers will respond to the changes in relative profitability of each and adapt their production methods. Such, private sector adaptation occurs quite naturally, and is difficult to distinguish from normal investment as such it is not modeled separately. Other forms of climate change affect the economy in such a way as the social benefits/costs of joint-action exceed those of private action: for example the social cost of flood-proofing a neighborhood might be well below the cumulative cost were all individuals to flood proof their own land independently. These public-sector adaptation investments are the kind tracked and modeled here.

#### 3.1.4.3 The Investment deflator

The long run level of the investment deflator is assumed to be a constant ratio of the consumption deflator. In the short run, the rate of growth of the investment deflator is a weighted average of nominal consumer inflation and its own lag, where the weight attached to past inflation ($\beta$) is estimated econometrically. Because no independent data on the price deflators for government investment as distinct from private investment nor for productive vs. adaptation investment exist, all four deflators are assumed to be equal:

$$\Delta p_t^{I,XN} = \alpha + \theta\left[p_{t-1}^{I,XN} - p_{t-1}^{C,XN}\right] + \beta \Delta p_{t-1}^{I,XN} + (1-\beta)\Delta p_t^{I,XN} + \varepsilon_t^{PI}$$

#### 3.1.4.4 Real government investment

Real government investment (productive and adaptation) is then an identity which equals the nominal variable divided by the investment deflator:

$$IGP_t^{KN} = \frac{IGP_t^{CN}}{P_t^{IG}} \; ; \; IA_t^{KN} = \frac{IA_t^{CN}}{P_t^{IG}}$$

### 3.1.5 Exports

#### 3.1.5.1 Real exports

Exports in the model are determined by foreign demand and relative prices (measured as the price of exports relative to domestic factor prices). Pakistan is modeled as a price taker using the small open economy assumption. The model equation for exports is the solution to an exporting firm's optimal export supply decision. Foreign demand ($XMKT_t$) is an index reflecting the weighted average of trading partners' ($k$) imports of goods and services (measured in USD $M_t^{KD^K}$), where the weights represent the historical share of Pakistan's exports going to each trading partner, and the index ($XMKT_t$) is set equal to national accounts exports in the base year $\left(XMKT_{base} = X_{base}^{KN}\right)$. This variable then grows in line with this weighted average of the trading partner imports:

$$XMKT_t = XMKT_{t-1}\left[1 + \sum_k^K \alpha_k \Delta m_t^{KD^K}\right]$$

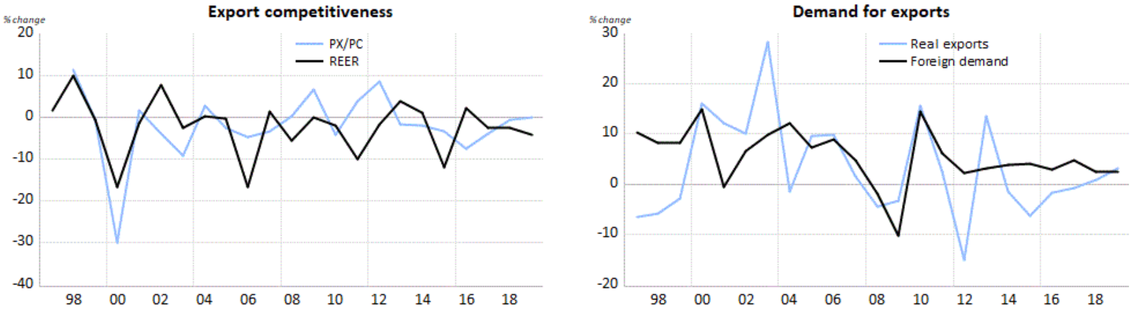
Having defined trade partner import demand, export volumes in the long run are a fixed share of this indexed export market demand and (de)increases if Pakistan becomes (less) more competitive, measured as an increase (decrease) in export prices relative to domestic production prices:

$$\Delta x_t^{KN} = \alpha + \theta\left[x_{t-1}^{KN} - \gamma_1 xmkt_{t-1} - \gamma_2 \ln\left(\frac{P_{t-1}^{X,XN}}{P_{t-1}^{fcst}}\right)\right] + \beta_1 \Delta xmkt_t + \beta_2 \Delta \ln\left(\frac{P_t^{X,XN}}{P_t^{fcst}}\right) + \varepsilon_t^X$$

In the long run $\gamma_1 = 1$ to ensure that exports grow in line with trading partners' demand. In the short run the elasticity of exports to export market growth can differ from 1 and is freely estimated $\beta_1$. Competitiveness increases when the price of exports rises relative to the domestic price by $\gamma_2$ in the long run.

The left panel in Figure 4 shows that the relative price of exports to domestic prices track the real effective exchange rate (reer) relatively well over time.

Figure 4: Determinants of exports in Pakistan



Source: Macro Poverty Outlook and own calculations

#### 3.1.5.2 Export deflator

The export deflator price depends on an export price index PXKEY), which is defined as the weighted average of the dollar price of ($l$) internationally traded commodities, where weights ($\alpha_l$), reflect the share of the commodity l in total commodity exports for 2011 such that $\sum_l \alpha_l = 1$, The index PXKEY is based to value 1 in the 2011:

$$PXKEY_t = \sum_l^L \alpha_l \left(\frac{PCOM_{t,l}}{PCOM_{2011,l}}\right)$$

The export price deflator is given by:

$$\Delta p_t^{X,XN} = \alpha + \theta\left[p_{t-1}^{X,XN} - \gamma_1 pxkey_{t-1} * fx_{t-1}^{PK,USD} - (1-\gamma_1)p_{t-1}^{fcst}\right] + \beta_1 \Delta\left(pxkey_t * fx_t^{PK,USD}\right) + \beta_2 \Delta p_t^{fcst} + \varepsilon_t^{PX}$$

In the long run domestic export prices grow in line with ($\gamma_1 = 1$) world prices (adjusted for the exchange rate) – ensuring convergence and that the law of one price holds. The short-run elasticity may differ ($\mathrm{B}_1 \neq 0$), and will reflect cost-push factors proxied by domestic inflation.

#### 3.1.5.3 Nominal exports

Nominal exports are determined by the product of the deflator multiplied by real exports:

$$X_t^{CN} = X_t^{KN} P_t^{X,XN}$$

### 3.1.6 Imports

#### 3.1.6.1 Non-energy imports

Final goods producers choose between non-energy domestic and imported goods by minimizing costs

$$\underbrace{min}_{M^{KN}_{OTH,t}} \left(P^{M,XN}_{OTH,t} M^{KN}_{OTH,t} + P^{XN}_{FD,t} FD^{KN}_t\right)$$

subject to a production function:

$$Y^{KN}_t = \left[\omega^M M^{KN,\rho}_{OTH,t} + \omega^{FD} FD^{KN,\rho}_t\right]^{\frac{1}{\rho}}$$

Non-energy imports depend on domestic demand (approximated as the sum of household and government consumption and investment) and the relative price of imports to domestic prices. This is consistent with the first order condition above of an importing firm minimizing costs by choosing an optimal mix of locally produced and imported goods.

An increase in import prices relative to domestic prices will lead to a reduction in import volumes. If domestic demand increases ($GDE^{KN} = C^{KN} + CG^{KN} + I^{KN}$), then imports will increase relative to the income elasticity:

$$\Delta m^{KN}_{OTH,t} = \alpha + \theta \left[m^{KN}_{OTH,t-1} - \gamma_1 ygde^{KN}_{t-1} + \gamma_2 \ln\left(\frac{P^{M,XN}_{OTH,t-1}}{P^{fcst}_{t-1}}\right)\right] + \beta_1 \Delta ygde^{KN}_t - \beta_2 \Delta \ln\left(\frac{P^{M,XN}_{OTH,t}}{P^{fcst}_t}\right) + \varepsilon^{MKN}_t$$

This equation ensures that the share of non-energy imports is fixed relative to final demand (under the constraint that $\gamma_1 = 1$).

### 3.1.6.2 Energy imports

The import of energy source $k$ is the residual once consumption and domestic production are determined,

$$M^{KN}_{k,t} = C^{KN}_{k,t} - Y^{KN}_{k,t}$$
$$M^{CN}_{k,t} = C^{CN}_{k,t} - Y^{CN}_{k,t}$$

Total energy imports are the sum of imports of commodity $k$:

$$M^{KN}_{E,t} = \sum_k M^{KN}_{k,t}$$

$$M^{CN}_{E,t} = \sum_k M^{CN}_{k,t}$$

The value of other imports is obtained from the quantity and price of other imports,

$$M^{CN}_{Oth,t} = M^{KN}_{Oth,t} * P^{M,XN}_{Oth,t}.$$

The value of total imports is then given as the sum of the two components,

$$M^{CN}_t = M^{CN}_{E,t} + M^{CN}_{Oth,t}.$$

#### *3.1.6.3 The non-energy import price deflator*

Non-energy prices of goods depend on an import price index (PMKEY), which is calculated as the weighted average of the world USD prices of imported commodities, converted into local prices, with the weights $\beta_l$ equal to the share of each $l_{th}$ commodity in total imports in 2011, with the index equaling 1 in 2011. Service imports are proxied by domestic prices on the assumption that firms price to the market:

$$\Delta p_t^{M,OTH} = \alpha + \theta\left[p_{t-1}^{M,OTH} - \gamma_1 pmkey_{t-1} * fx_{t-1}^{PK,USD} * (1+\tau_{t-1}^{M}) - (1-\gamma_1)p_{t-1}^{fcst}\right] + \beta_1\Delta\left(pmkey_t * fx_t^{PK,USD}\right) + \beta_2\Delta p_t^{fcst} + \Delta\tau_t^M + \varepsilon_t^{PX}$$

$$PMKEY_t = \sum_{l}^{L}\beta_l\left(\frac{PCOM_{t,l}}{PCOM_{2011,l}}\right)$$

#### *3.1.6.4 Aggregate import price deflator*

Given that we have energy imports in both nominal and real values as well as non-energy values and volumes, aggregate import prices are then simply calculated as:

$$P_t^{M,XN} = \left(\frac{M_{Oth,t}^{CN} + M_{E,t}^{CN}}{M_{Oth,t}^{KN} + M_{E,t}^{KN}}\right)$$

### 3.2 GDP: Production measure

GDP from the production side (GDP at factor costs) equals the sum of agriculture $\left(Y_{AGR,t}^{KN}\right)$, services $\left(Y_{SRV,t}^{KN}\right)$, non-energy industry $\left(Y_{IND,t}^{KN}\right)$ and energy value-added $\left(Y_{E,t}^{KN}\right)$,

$$Y_{FCST,t}^{KN} = Y_{AGR,t}^{KN} + Y_{SRV,t}^{KN} + Y_{IND,t}^{KN} + Y_{E,t}^{KN}$$

Adding net indirect taxes less subsidies ($NIT_t^j$) to GDP at factor costs equals GDP at market prices (derived as the sum of consumption, investment, exports less imports),

$$Y_t^j = Y_{FCST,t}^j + NIT_t^j$$

An important modeling consideration is the mapping of demand and supply components to value-added. Ideally one would model the factor input choices in each sector. To do this requires data on labor, capital, rental rates and wages on a sectoral level. Unfortunately, time series data for these variables are typically not available for most countries.[11] Many macrostructural models neglect this part of the model by either omitting the value-added block entirely or by writing this block as reduced forms, with an identity determining the level of each sector.

In the current model, given differences in the energy consumption of different economic sectors and the importance of price signals to production decisions, a detailed economic modeling of decision making at the sectoral level is desirable.

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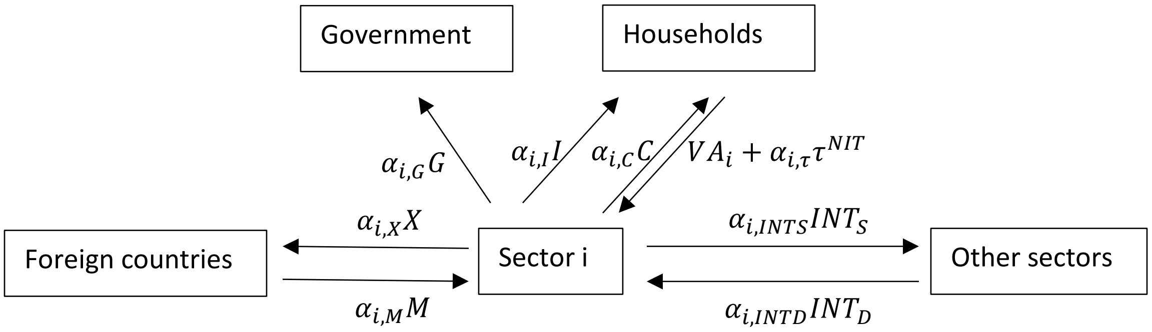
[11] In CGE models, a single point in time estimate is required, with other time periods generated by the model, with no assurance that they are actually equal to the unrecorded historical values (or different from the historical data in cases where they do exist).

The model uses data from the input-output (IO) table which provides more details about intermediate demand between sectors and the composition of final demand across sectors. The IO table maps the different intermediate products (notably energy projects) used to produce the goods and services that comprise final demand. By using the technical coefficients from this table (how many units of electricity and coal are needed to produce a unit of transportation) and time series data for final demand and aggregate sectors, we are able to generate pseudo time series for the intermediate demands of each sector (assuming that the technology of production is constant over time).

The technical relationships between elements of final demand and sectors of production that are summarized by the IO table are illustrated in the following diagram, which focuses on a single sector i.



Effectively, one unit of demand for exports will imply $\alpha_{i,X}$ units of final demand for the output of sector I, which in turn would generate $\alpha_{i,X} * \ \alpha_{j,i}$ units of intermediate demand for the output of each sector j. In this way each component of expenditure GDP is shared out to individual sectors. E.g. the exports of sector $i$ are written as the share of total exports, given by $\alpha_{i,X}$. It is important that $\sum_i \alpha_{i,X} = 1$, such that all of exports are shared out. Imports are given by $M$. The intermediate goods supplied to and demanded from the other sectors is denoted as $INT_S$ and $INT_D$, respectively. In addition, sector $i$ supplies government consumption $G$, investment goods $I$ and consumption goods $C$. Value added ($VA$) and indirect taxes ($\tau^{NIT}$) correspond to the value of capital and labor provided by households (or equal to GDP from the income side, although without capital and labor data, respectively). The equations for total source (on the left of the equation) and total use (on the right of the equation) with the equilibrium condition of Supply = Demand imposed can be written as,

$$VA_i + \alpha_{i,\tau}\tau^{NIT} + \alpha_{i,M}M + \alpha_{i,INTD}INT_D = \alpha_{i,C}C + \alpha_{i,I}I + \alpha_{i,G}G + \alpha_{i,X}X + \alpha_{i,INTS}INT_S.$$

For the purposes of this model there is no need to include all the intermediate demands generated for each final demand (the number of variables expands by the number of sectors and for each price, quantity and value equivalents). Instead we focus on the intermediate demands for energy from each sector but lump together all other intermediate demands. As is customary in CGE models, we assume a Leontief technology (fixed ratio) for intermediate demands, which implies that the share of intermediate supply to aggregate supply is constant over the policy and forecast horizons. We define these ratios as:

$\beta_{i\neq Energy} = \frac{INT^{D}_{i,non-energy}}{VA_i}$ = share of non-energy intermediate goods in total inputs for sector *i*

$\gamma_i = \frac{\alpha_{i,INTS}INT_S}{\alpha_{i,C}C+\alpha_{i,I}I+\alpha_{i,G}G+\alpha_{i,X}X}$ = share of use of goods *I* as intermediate inputs in total uses

$$\zeta_i = \frac{INT^D_{i,energy}}{VA_i}$$ = share of energy inputs in total inputs for sector *i*

Note that $INT^D_{i,energy} + INT^D_{i,non-energy} = \alpha_{i,INTD} INT_D$

With these ratios we can rewrite value-added as

$$VA_i^{simul} = \frac{\left((1+\gamma_i)\left(\alpha_{i,C}C + \alpha_{i,I}I + \alpha_{i,G}G + \alpha_{i,X}X\right) - \alpha_{i,\tau}\tau^{NIT} - \alpha_{i,M}M\right)}{(1+\beta_i+\zeta_i)}.$$

The equation above connects each industry's value-added to the demand side of the economy. Thus, simulations that affect demand will be passed onto industry value-added.

Value-added in the national accounts and in the SAM will be equal to each other in the year of the available SAM, $VA^{simul}_{i,t=SAM} = Y^{NIA}_{i,t=SAM}$, but in other years the relationship will not hold exactly, due to changing patterns of demand that would shift weights. However, these time varying weights are not available. To account for shifts in non-SAM years we rewrite the above in an error-correction form for value-added as:

$$\Delta\ln\left(Y^{NIA}_{i,t}\right) = \theta_i\left[\ln\left(Y^{NIA}_{i,t-1}\right) - \ln\left(VA^{simul}_{i,t-1}\right)\right] + \beta\Delta\ln\left(VA^{simul}_{i,t}\right) + \varepsilon^Y_t$$

Note that $Y_{i,t}$ is the national accounts equivalent of value-added for sector $i$ (for which time series data are available. The equation above maps these data to the IO equivalent of value added, $VA_{i,t}$. This formulation ensures that the growth in actual value-added is equal to the growth in GDP (in steady state) while deviations in the short-run are gradually corrected for $-1 < \theta_i < 0$. Unless there are structural shifts in aggregate demand the shares of value-added historically are maintained in the forecast period. With this formulation, the sum of the value-added variables equals GDP at factor prices ($Y^j_{FCST,t} = \sum_i Y_{i,t}$) and the difference between GDP at market prices and factor prices is equal net indirect taxes and subsidies ($Y^j_t - Y^j_{FCST,t} = \tau^{NIT}_t = \sum_i \alpha_{i,\tau}\tau^{NIT}_t$).

This framework forms the basis of how energy is added and modeled. Of interest is an appropriate mapping of energy demand to what is supplied. This is discussed in more detail below.

### 3.2.1 The energy sector

The energy sector is of particular importance for climate change mitigation because several energy sources are major sources of carbon and other GHG emissions and because the carbon intensity of different sources of energy are very different. In the model energy is produced by coal, oil, gas and renewables (electricity is modeled as a derived form of energy produced by a mixture of these inputs), with separate prices, taxes and production functions for each.

Since different energy sources have different carbon intensities, changes in the price of carbon (carbon tax and or changes in commodity-specific subsidies) may cause a substitution from high carbon to low carbon technologies.

The following sub-sections explain how prices (inclusive of subsidies/carbon taxes) and quantity data are created and then embedded into firm and household optimization decisions.

#### 3.2.1.1 Available data on quantities and prices

Energy related data are sourced from the IEA database "World energy balances", which is available from the OECD (https://www.oecd-ilibrary.org/).[12]

In the model, we aggregate energy into four categories: coal (15.2% of the energy mix in 2017), oil (40.5%), natural gas (36.9%), and "renewables" (7.5%). The "renewables" category includes nuclear power, hydro, solar and wind. While nuclear power is not renewable, all these energy sources have in common that their net carbon emissions are zero or very low. A carbon price would thus not directly affect this energy category. In addition to the 55,561 kilotons of oil equivalent (ktoe) used from the energy sector, Pakistani households also used 30,187 ktoe from biofuels in 2011. Biofuels data are not included in the model due to a lack of macroeconomic data. From a carbon accounting point of view the omission is not serious as biomass is a "carbon neutral" energy source when managed well (Favero, Daigneault, and Sohngen 2020), although it can make a significant contribution to local air pollution. Biomass first absorbs carbon from the atmosphere (when a tree grows, for example) and then releases it again (when wood is burned).

The IEA provides data on energy produced, imported and exported and the shares of fuel type in electricity generation. The data are available in kilotons of oil equivalent (ktoe). While Pakistan exports some oil products, it is a net importer in every energy category, so that we bundle exports and imports as "net imports". We denote energy produced by Pakistan (in ktoe) as $Q_t^k$ with $k$ indicating the category (coal, oil, gas, renewable). Net imports are denoted as $Q_{k,t}^M$, while energy commodities consumed in the production of electricity is denoted as $Q_{k,t}^{Elec}$.

Historical market price data for energy is sourced from the World Bank's commodity sheets (pink sheets). These are denoted as $P_{k,t}^{USD}$. The units of the prices are USD per metric ton (USD/mt) for coal, USD per barrel (USD/BBL) for oil and USD per one million British thermal units (USD/MMBTU). The following conversions are applied to make the units between prices and quantities compatible: $\beta^{coal} = 1.429\,\frac{mt}{toe}$, $\beta^{oil} = 7.4\,\frac{BBL}{toe}$ and $\beta^{gas} = 39.683\,\frac{mmbtu}{toe}$. The International Renewable Energy Agency (IRENA) provides data on renewable energy. Given that historically the largest energy source in the "renewable" category is hydropower, we use the price of hydropower as a proxy for the category historically.[13] For local currency conversion we use the rupee- U.S. dollar exchange rate, $fx_t$. Electricity prices are usually denoted as cents per Kwh, however, for consistency here they are scaled to reflect the price per ton of oil equivalent.

In recent years, fossil fuels have been sold below their respective world market prices in Pakistan. While there are plans to reduce or abolish subsidies, fuel subsidies still amounted to a total of 3.4 USD billion in 2017 or 1.14% of GDP according to IEA data. In the model, subsidies on fuel are represented as negative carbon taxes. In the modeling, it is assumed that the government is not transferring funds to energy producers, and hence it is not a direct expenditure but rather a forgone revenue that it would have collected. The fiscal accounting from a debt and overall balance perspective would have been equivalent if it was accounted for as an expenditure. Mitigation policy can take the form of increasing carbon taxes, from the current negative values to zero and then to positive values. Carbon taxes ($\tau_t^k$) are expressed as USD per ton of $CO_2$ (USD/t). As indicated by the subscript $t$, carbon taxes are time-variant. The distinction

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[12] All data used in this model can be traced to the original data through the Excel workbook "Pakistan energy and emission data.xlsx".

[13] The Pakistani government provides detailed data on renewable energy prices in the "Indicative Generation Capacity Expansion Plan". We are planning to update the model with these data.

of energy type $k$ is necessary since the subsidies vary across energy sources. Furthermore, electricity subsidies are netted out of carbon subsidies.

To calculate the fossil fuel subsidy (or negative carbon tax) per energy source, we use IEA data (for the period 2010 to 2019) and IMF data (for 2007 to 2009) on the total amount of subsidies paid for each of the three energy sources and electricity. Subsidies for electricity are described in more detail below. We use data on the total amount of emissions from each fuel type. Fossil fuel subsidies for energy type $k$ divided by total emissions from energy type $k$ provides the subsidies for energy type $i$ per ton of $CO_2$. The data for 1980 to 2006 are calculated using the average share of subsidies in the world market price.

The taxed quantities are the energy sources in ktoe. In order to obtain the tax per ktoe we need a conversion coefficient, denoted as $\alpha^k$. It will be in units of tons of $CO_2$ per kiloton of oil equivalent (t/ktoe). Following (Carrara and Marangoni 2017), we obtain the following values: $\alpha^{coal} = 2.26 \frac{t}{ktoe}$, $\alpha^{oil} = 1.75 \frac{t}{ktoe}$, $\alpha^{gas} = 1.34 \frac{t}{ktoe}$ and $\alpha^{ren} = 0 \frac{t}{ktoe}$.

### 3.2.1.2 Constructing the energy variables used in PAKMod

Because we want to track the carbon and other GHG emissions associated with energy production from different sources, the model needs to account for energy volumes both in terms of physical quantities as well as the more traditional national accounting volumes derived from base-year values and market or factor-price deflators. We construct the national account equivalent variables in the model using the data above.

Energy prices and the valuation of energy value added is complicated by the mechanisms by which fuels are subsidized in Pakistan. Historically, crude oil and natural gas are purchased by the government in international markets at market prices ($P_{k,t}^{USD}$), and then sold to firms at a lower fixed cost. The final domestic market price at which firms are allowed to sell products is also fixed by the government. This implicit subsidy to consumers is represented in the model as a negative carbon tax.

In the model, the nominal market value of each fuel type produced is given by

$$\hat{Y}_{k,t}^{CN} = Q_{k,t} * FX_t\left(P_{k,t}^{USD} * \beta^k + \tau_t^k * \alpha^k\right).$$

where $\hat{Y}_{k,t}^{CN}$ is the amount paid by the firm when purchasing the energy source , and $Q_{k,t}$ represents the physical quantity produced (and sold) in kilotons of oil equivalent (ktoe). The remainder of the expression reflects the market price of energy in local currency and is the product of the exchange rate and the international market price in USD in barrels, or cubic meters multiplied by a conversion factor $\beta^k$ (which converts the USD price per commodity unit (say Barrel) to a USD price per ktoe). The final expression reduces (or increases) the international price by the amount of the implicit subsidy (or carbon tax). Where the carbon tax /subsidy rate ($\tau_t^k$) is in USD per ktoe of $CO_2$. where $\alpha^k$ converts the commodity quantity into ktoe of carbon.

Since the prices above are inclusive of taxes and subsidies, they are consistent with the market price deflators of national accounts, as opposed to factor-price deflators. We write output measured in this way with a superscript hat to differentiate it from sectoral value added and output at factor costs, which is typically produced in the national accounts. Gross output at factor cost should be given by

$$Y_{k,t}^{CN} = \hat{Y}_{k,t}^{CN} * \left(1 - \tau_t^k * \alpha^k\right) - \alpha_{E,\tau}\tau^{NIT}$$

And factor cost value added should be given by:

$$Y_{E,t}^{CN} = \sum_k \hat{Y}_{k,t}^{CN} - (\zeta_E + \beta_E)VA_E^{CN} - \alpha_{E,M}M$$

Where $(\zeta_E + \beta_E)$ is the sum of the weights of all intermediates used in the energy sector, and $\alpha_{E,\tau}\tau^{NIT} - \alpha_{E,M}M$ reflects net indirect taxes and imports of each energy type.

In practice, the factor cost value of sectoral output calculated in this way does not correspond exactly to the value-added data reported in the national accounts.

To harmonize the two data sources, we calculate following scaling factor:

$$\gamma_t^{CN} = \frac{Y_{E,t}^{CN}}{\sum_k \hat{Y}_{k,t}^{CN} - (\zeta_E + \beta_E)VA_E^{CN} - \alpha_{E,\tau}\tau^{NIT} - \alpha_{E,M}M}$$

An exact match will thus be enforced by setting

$$Y_{k,t}^{CN} = \gamma_t^{CN} * \left(\sum_k \hat{Y}_{k,t}^{CN} - (\zeta_E + \beta_E)VA_E^{CN} - \alpha_{E,\tau}\tau^{NIT} - \alpha_{E,M}M\right).$$

In the forecast period $\gamma_t^{CN}$ is held constant.

The preliminary price index (based in 2011) for each fuel type (the $XN$ variable in PAKMod mnemonics) is given by

$$\hat{P}_{k,t}^{XN} = \frac{\left(FX_t * P_{k,t}^{USD} * \beta^k + \tau_t^k * \alpha^k\right)}{\left(FX_{2011} * P_{k,2011}^{USD} * \beta^k + \tau_{2011}^k * \alpha^k\right)}.$$

The national accounting parts of PAKMod records quantities not in physical units (such as ktoe), but in constant prices. A similar scaling factor is used to reconcile the modeled NIA volume data.

Modeled volumes are given by:

$$\hat{Y}^{KN}{}_{k,t} = \frac{\hat{Y}_{k,t}^{CN}}{\hat{P}_{k,t}^{XN}}.$$

For the $\hat{Y}_{k,t}^{KN}$ we also need to calculate a scaling factor,

$$\gamma_t^{KN} = \frac{Y_{E,t}^{KN}}{\sum_k \hat{Y}_{k,t}^{KN} - (\zeta_E + \beta_E)VA_E^{CN} - \alpha_{E,\tau}\tau^{NIT} - \alpha_{E,M}M}.$$

Using the scaling factors, we obtain the "harmonized" data for the energy sources,

$$Y_{k,t}^{KN} = \gamma_t^{KN}\left(\sum_k \hat{Y}_{k,t}^{KN} - (\zeta_E + \beta_E)VA_E^{CN} - \alpha_{E,\tau}\tau^{NIT} - \alpha_{E,M}M\right).$$

Using the current and constant value for each energy source, we obtain the NIA price index as

$$P_{k,t}^{XN} = \frac{Y_{k,t}^{CN}}{Y_{k,t}^{KN}}.$$

#### 3.2.1.3 Integrating the energy sector into the IO table structure

The production by energy types does not have an exact correspondence in the IO table. The link is thus created by mapping the energy types to the energy sector.

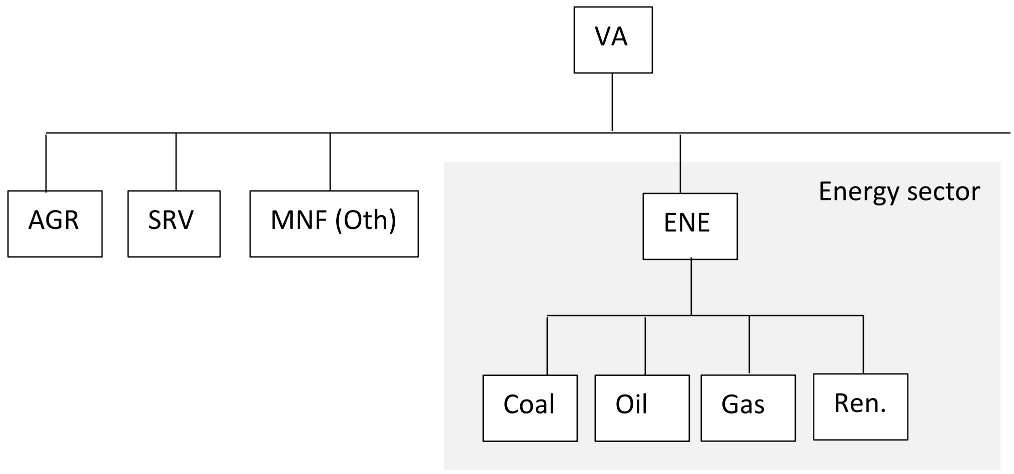
The IO contains four energy related product categories, as listed in the table below.

| Sector | Sub-sector | Product |
|---|---|---|
| **Manufacturing** | Mining | Coal and Lignite; and Peat |
| **Manufacturing** | Mining | Crude Petroleum and Natural Gas (Distribution through Main) |
| **Manufacturing** | Manufacturing | Electricity, Town Gas, Steam, and Hot Water and Natural Water |
| **Manufacturing** | Manufacturing | Coke Oven Products; Refined Petroleum Products; and Nuclear Fuel |

The supply and use tables show that the two mining sectors sell their output mostly to the refining sector. We thus consider the bottom two sectors from the table as the energy sector for the purpose of this project. Total value added will thus be given by

$$Y_{FCST}^{KN} = VA = Y_{AGR,t}^{KN} + Y_{SRVt}^{KN} + Y_{IND,t}^{KN} + Y_{E,t}^{KN},$$

Which correspond to agriculture (AGR), services (SRV), non-energy manufacturing (MNF(Oth)), and "energy" (ENE). The energy sector uses fossil fuels and renewables so that we obtain the following nested CES structure.



Note that the sectoral split can be more detailed. For example, transport as a sector could be broken out from the service sector. Doing so would allow energy price effects to impact costs, prices and ultimately production in the transportation sector with potentially interesting outcomes. The mapping from demand to activities imply that energy is determined from a top-down approach. There are other approaches that can be explored with more detailed data. One can "soft-link" detailed engineering energy systems with a macro model. This approach requires that the supply potential of the detailed energy model interacts with the demand components of the macro model to determine prices and investment quantities. In PAKMod, one can switch off the reduced-form energy block to integrate the outputs from the energy model. To model the transportation sector would require that energy be split into those activities used for transportation and those that are used for other things. This would also require a direct mapping from demand to transportation. Our modeling above lumps all of this into an aggregate energy sector.

#### 3.2.1.4 Energy imports

We need to construct the energy and non-energy components of imports before estimation. The value of imports for each energy type and total energy imports is given as

$$M_{k,t}^{CN} = Q_{k,t}^{M} * FX_t\left(P_{k,t}^{USD} * \beta^k + \tau_t^k * \alpha^k\right)$$

$$M_{E,t}^{CN} = \sum_k M_{k,t}^{CN}$$

The constant value of imports is obtained with the price index determined from the production side,

$$M_{k,t}^{KN} = \frac{M_{E,t}^{CN}}{P_{k,t}^{XN}},$$

$$M_{E,t}^{KN} = \sum_k M_{k,t}^{KN}.$$

The deflator for energy imports is given by

$$P_{E,t}^{M,XN} = \frac{M_{E,t}^{CN}}{M_{E,t}^{KN}} = P_{k,t}^{XN}$$

In addition to the energy imports, we calculate non-energy imports as the residual from total imports,

$$M_{Oth,t}^{CN} = M_t^{CN} - \sum_k M_{k,t}^{CN}$$

$$M_{Oth,t}^{KN} = M_t^{KN} - \sum_k M_{k,t}^{KN}$$

$$P_{Oth,t}^{M,XN} = \frac{M_{Oth,t}^{CN}}{M_{Oth,t}^{KN}}$$

#### 3.2.1.5 Energy demand

The constant and nominal values of energy demand is the sum of domestically produced energy, net imported energy and indirect taxes (assuming that energy is neither consumed by the government nor exported). The variable $T^{Ind}$ is the total amount of indirect taxes collected by the government of Pakistan.

The energy sector contributes a significant amount to net indirect taxes and subsidies as recorded in the IO table. Roughly 51% of indirect taxes and subsidies accrue from the energy sector.

$$C_{E,t}^{KN} = Y_{E,t}^{KN} + M_{E,t}^{KN} - 0.51 * T^{Ind,KN},$$

$$C_{E,t}^{CN} = Y_{E,t}^{CN} + M_{E,t}^{CN} - 0.51 * T^{Ind,CN},$$

$$P_{E,t}^{C,XN} = \frac{C_{E,t}^{CN}}{C_{E,t}^{KN}}.$$

Other consumption is the residual of total private consumption and energy consumption:

$$C_{oth,t}^{KN} = C_t^{KN} - C_{E,t}^{KN},$$

$$C_{oth,t}^{CN} = C_t^{CN} - C_{E,t}^{CN},$$

$$P_{oth,t}^{C,XN} = \frac{C_{oth,t}^{CN}}{C_{oth,t}^{KN}}.$$

After having compiled consumption of commodity type $k$, we then split these consumption amounts into electricity and non-electricity consumption. The total value of electricity consumption is the sum of each commodity used in electricity multiplied by the international price in local currency units:

$$C_{Elec,t}^{CN} = P_{Elec,t}^{C,XN} C_{Elec,t}^{KN} = \sum_k P_k^{Elec} Q_{k,t}^{Elec}$$

Non-electricity consumption is the residual after subtracting electricity consumption from total energy consumption:

$$C_{OE,t}^{CN} = C_{E,t}^{CN} - C_{Elec,t}^{CN}$$

#### 3.2.1.6 The price index for the aggregate energy sector

To calculate the various energy weights into production and consumption using a CES form, we first need to estimate the elasticities of substitution. The elasticities of substitution between different commodity types are estimated using a trans-log function:

$$\ln(c_t) = \alpha + \beta_Y \ln(Y_t) + \sum_k \beta_k \ln\left(w_{k,t}\right) + \frac{1}{2} \sum_k \sum_j \gamma_{kj} \ln(w_k) \ln\left(w_j\right) + \frac{1}{2} \beta_{YY} \ln(Y_t)^2 + \sum_k \gamma_k \ln(w_k) \ln(Y_t) + e_t$$

Where the cost is denoted as $c_t = Y_{E,t}^{KN} P_{E,t}^{XN}$ and $w_{k,t}$ are the prices of energy, while $e_t \sim N(0, \sigma^2)$.

This system of equations gives us the cross elasticity of substitution: $\rho^{kj} = \frac{\gamma_{kj} + \theta^k \theta^j}{\theta^k}$ or the elasticity of substitution is $\sigma^{kj} = \frac{\rho^{kj}}{\theta^k} + 1$ where $\theta^k = \frac{P_{k,t}^{XN} Y_{k,t}^{KN}}{Y_{E,t}^{KN} P_{E,t}^{XN}}$ are the expenditure shares.

The estimated elasticity of substitution is 1.2 and we assume that they hold for production and consumption: $\sigma^{Prod} = \sigma_3 = \sigma_4 = 1.2$. Some estimates suggest that the elasticity of substitution between different commodity types can be as large as 5 (Carrara and Marangoni 2017). These estimates matter significantly when quantifying the impact of a carbon price policy. The modeling simulations illustrate the sensitivity of results to various elasticity choices. For the baseline, the estimates of Carrara and Marangoni (2017) were used.

With the elasticity of substitution estimated we can calculate the effective shares of energy production by commodity type:

$$\omega_k^{Prod} = \left(\frac{Y_{k,t}^{KN}}{Y_{E,t}^{KN}}\left(\frac{P_{k,t}^{XN}}{P_{E,t}^{Index}}\right)^{\sigma^{Prod}}\right)^{\frac{1}{\sigma^{Prod}}}$$

Using these shares, we can calculate the gross price index of energy. This price index includes the carbon price and thus ensures that consumers adjust their energy consumption to changes in the tax (as well as to changes in the international price of the energy sources):

$$P_{E,t}^{XN} = \left(\sum_k \left(\omega_k^{Prod}\right)^{\sigma^{Prod}} \left(P_{k,t}^{XN}\right)^{1-\sigma^{Prod}}\right)^{\frac{1}{1-\sigma^{Prod}}}$$

### *3.2.1.7 Sectoral prices*

Non-energy sectoral prices in the model are a function of factor prices, while energy prices are determined in global energy markets. Unfortunately, we do not have detailed investment, capital and labor data over time per sector. Thus, marginal costs in each sector are derived from aggregate marginal costs and aggregate producer prices. This implies that producer inflation is modeled first and then mapped to the individual sector deflators.

The producer price deflator is a function of nominal marginal costs (a weighted average between wages and the cost of capital), persistence and expectations, additionally in the short-run producer prices rise (fall) in response to a positive (negative) output gap):

$$\Delta p_t^{fcst} = c + \theta\left[p_{t-1}^{fcst} - mc_{t-1}\right] + \gamma \Delta p_{t-1}^{fcst} + (1-\gamma)(\lambda \Delta mc_{t-1} + (1-\lambda)\pi_t^e) + \beta\left(\frac{Y_t}{Y_t^*} - 1\right) + \varepsilon_t^{Pfcst}$$

Additional inflationary pressures of $\beta$ are generated when demand exceeds supply. Wage pressures or an increase in capital costs also increases inflation. Note that $\lambda$ measures the degree to which factor price inflation is indexed to marginal costs vs. expected inflation ($\pi_t^e$). In the long-run producer prices grow in line with expected inflation, which converges to the inflation target. This is because nominal wages and capital grow at the rate of the inflation target in the long-run (where real wages grow in line with labor productivity – see discussion below).

### *3.2.1.8 Equations for the energy sector*

The derived demand for energy from source $k$ is determined in a constrained optimization problem by energy producers where commodities are substitutes and expressed using a CES production function:

$$Y_{E,t}^{KN} = \left(\sum_k \omega_k^{Prod}\, Y_{k,t}^{KN\rho}\right)^{\frac{1}{\rho}}$$

Subject to $Y_{E,t}^{KN} P_{E,t}^{XN} = \sum_k Y_{k,t}^{KN} P_{k,t}^{XN}$. The standard demand for energy $k$ is then given as:

$$Y_{k,t} = \left(\omega_k^{Prod}\right)^{\sigma^{Prod}} \left(\frac{P_{E,t}^{XN}}{P_{k,t}^{XN}}\right)^{\sigma^{Prod}} Y_{E,t}^{KN}$$

where $\sigma^{Prod} = \frac{1}{1-\rho}$. Thus, at the top level, the demand for energy is derived from:

$$Y_{E,t}^{KN} = \frac{(1+\gamma_E)\left(\alpha_{E,C} C_t^{KN} + \alpha_{E,I} I_t^{KN} + \alpha_{E,G} CG_t^{KN} + \alpha_{E,X} X_t^{KN}\right) - \alpha_{E,\tau}\tau^{NIT} - \alpha_{E,M} M_t^{KN}}{1 + \beta_E + \zeta_E}$$

### 3.2.1.9 Adjustment to alternative energy sources accounting for high fixed costs

A real-world complexity encountered in mitigation scenarios is that for many energy sources the fixed cost of power plants is quite high, and the variable costs of running them relatively low. As a result, even in the face of high carbon taxes as long as the market price less the carbon tax exceeds the variable cost of producing energy, firms may continue to use high carbon plants (even though they would no longer build new ones). As a result, the transition to new low carbon energies could be relatively slow. Many energy models take this information into account in order to estimate the speed of adjustment. Fofrich *et al.* (2020) indicate that coal-fired power plants are retired one to three decades earlier than they would be in the absence of carbon pricing in scenarios aimed at limiting global warming to between 1.5 and 2.0 degrees Celsius.

The solution to the long run optimization problem PAKMod indicates the level of production that would be observed after all adjustments take place, primarily reflecting the elasticity of demand as well as the general economic response. To approximate the slower than immediate retirement of high-carbon assets, PAKMod employs a reduced form error correction approach with the speed of adjustment in energy production calibrated to ensure that 30 percent of the equilibrium adjustment is achieved annually.

More specifically, output of energy $k$ is modeled as:

$$\Delta \ln\left(Y_{k,t}\right) = \ln\left(\omega_k^{Prod^{\sigma^{Prod}}}\right) + \theta\left[\ln\left(Y_{k,t-1}\right) - \sigma^{Prod}\ln\left(\frac{P_{E,t-1}^{XN}}{P_{k,t-1}^{XN}}\right) - \ln\left(Y_{E,t-1}^{KN}\right)\right] + \beta_1 \ln\left(\frac{P_{E,t}^{XN}}{P_{k,t}^{XN}}\right) + \beta_2 \ln\left(Y_{E,t}^{KN}\right) + \varepsilon_t^{Y_k}$$

The equation above distinguishes the short run from the long run. A change in the carbon price will affect energy production from fossil fuels by $\beta_1$ in the short term. Fossil fuel production thus slows in the long run, but not fully as in a static environment. In the long run (measured by $\frac{1}{|\theta|}$), fossil fuel production slows by $\sigma^{Prod}$.

## 3.3 The labor market

As much as 90 percent of the labor force in Pakistan operates in the informal sector (defined as individuals without formal employment contracts and without access to social security).

Firms are modeled as making the choice to engage in a formal or an informal contract after weighing the advantages and disadvantages of each employment type. Major benefits of the formal sector are access to financial services and government services. A major benefit of being in the informal sector is that firms can avoid direct taxation by the government.

This firm's decision is captured in heterogeneous firm models as presented in Ulyssea (2018), where firms differ by productivity. Very productive firms tend to be larger than less productive firms and thus benefit from returns to scale. More productive and larger firms, therefore, tend to enter the formal market while less productive firms produce informally. In Appendix 1A, we present a simplified version of the model in Ulyssea (2018). This theoretical result has been supported by several empirical papers finding that reducing labor taxes increases formal employment (Rocha, Ulyssea, and Rachter 2018; Bosch and Esteban-Pretel 2012; Ulyssea 2010).

Integrating the model from Appendix 1A into PAKMod would be a conceptually convincing solution. However, any calibration would be very uncertain, and would require firm-level data on the distribution of firm sizes (both formal and informal).

Therefore, we follow Ahmed (2012) and assume that informal and formal labor can be combined in a constant elasticity of substitution (CES) function to total labor, $N_t = \left[\beta^F {N_t^F}^{\sigma} + \beta^I {N_t^I}^{\sigma}\right]^{\frac{1}{\sigma}}$.

### 3.3.1 Data creation

The International Labour Organization provides data for the share of formal employment in total employment (ILO 2020b). This variable, denoted as $s_t^{N,I}$, allows calculating the historical values for formal and informal employment,

$$N_t^F = \left(1 - s_t^{N,I}\right) * N_t,$$

$$N_t^I = s_t^{N,I} * N_t,$$

where total employment, $N_t$, is available in MFMod.

The budget constraint is given as $W_t N_t = (1 + \tau_t^N) W_t^F N_t^F + W_t^I N_t^I$, where $W_t$ is aggregate wealth, $W_t^F$ is the net wage paid for formal labor and $W_t^I$ is the wage paid for informal labor. The first order condition for the informal sector can then be written as

$$W_t^I = \beta^I \left(\frac{N_t}{N_t^I}\right)^{\sigma} W_t.$$

Based on the estimates in Table 1 of Ahmed (2012), we assume $\beta^F = 0.29$, $\beta^I = 1 - \beta^F = 0.71$ and $\sigma = 2$.

Available data for Pakistan, do not separate out direct taxes for labor and capital, so that we need to assume that the same tax rate applies to both labor and capital. The effective direct tax rate is thus

$$\tau^N = \frac{T_t^D}{(N_t W_t - N_t^I W_t^I) + GOS_t},$$

where $GOS_t$ is the gross operating surplus, a measure for capital income.

With this, we can calculate the formal wage rate as

$$W_t^F = \frac{W_t N_t - W_t^I N_t^I}{(1 + \tau_t^N) N_t^F}.$$

The wage bills for the formal and informal sector is

$$WB_t^F = (1 + \tau_t^N) W_t^F N_t^F,$$

$$WB_t^I = WB_t - WB_t^F.$$

The share of the wage bill from the informal sector in GDP is given by

$$s_t^{WB,I} = \frac{WB_t^I}{Y_t}.$$

### 3.3.2 Model equations

In a first step, we determine wages as an error correction model (ECM) equation. The equation is based on the marginal product of labor, $W_t^F = P_t^{FCST} \beta^F \left(\frac{Y_t}{N_t^F}\right)^{1-\rho}$ and $W_t^{IF} = P_t^{FCST} \beta^I \left(\frac{Y_t}{N_t^I}\right)^{1-\rho}$, where $P_t^{FCST}$ is the deflator for GDP at factor cost and $\alpha_F$ and $\alpha_{IF}$ are the labor shares for formal and informal employment, respectively. Taking logs and rearranging to reach the ECM form we obtain $\Delta \mathrm{w}_t^S = \left[w_{t-1}^S - p_{t-1}^{FCST} - (1-\rho)\ln\left(\frac{\alpha Y_{t-1}}{N_{t-1}^S}\right)\right] + \Delta p_t^{FCST} + (1-\rho)\Delta \ln\left(\frac{\alpha Y_t}{N_t^S}\right)$ and the analogous for the informal sector. This is then extended to the econometric equations implemented in the model:

$$\begin{aligned}\Delta w_t^F = c_1 - \theta^F * \left[w_{t-1}^F - p_{t-1}^{FCST} - (1-\rho)\ln\left(\frac{Y_{t-1}^*}{N_{t-1}^*}\right)\right] + \beta_1 * \Delta w_{t-1}^F + (1-\beta_1) \\ * \left[\left(0.5 * \Delta p_{t-1}^{FCST} + 0.5 * \pi_t^e\right) + (1-\rho)\Delta \ln\left(\frac{Y_t}{N_t^*}\right)\right] - \beta_2 * (UNR_t - UNR_t^*),\end{aligned}$$

$$\begin{aligned}\Delta w_t^I = c_1 - \theta^I * \left[w_{t-1}^I - p_{t-1}^{FCST} - (1-\rho)\ln\left(\frac{Y_{t-1}^*}{N_{t-1}^*}\right)\right] + \beta_1 * \Delta w_{t-1}^I + (1-\beta_1) \\ * \left[\left(0.5\Delta p_{t-1}^{FCST} + 0.5\pi_t^e\right) + (1-\rho)\Delta \ln\left(\frac{Y_t}{N_t^*}\right)\right] - \beta_2 * (UNR_t - UNR_t^*).\end{aligned}$$

Here, $Y_t^*$ is potential GDP, $N_t^*$ is structural employment, $\pi_t^e$ is inflation expectation, $UNR_t$ is the unemployment rate and $UNR_t^*$ is structural unemployment.

We assume that informal and formal labor can be aggregated in a CES function given by $N_t = \left[\beta^F {N_t^F}^{\sigma} + \beta^I {N_t^I}^{\sigma}\right]^{\frac{1}{\sigma}}$. The first order conditions determine the employment outcomes as:

$$N_t^F = (\beta^F)^\sigma \left(\frac{W_t}{W_t^F(1+\tau^N)}\right)^\sigma N_t,$$

$$N_t^I = (\beta^I)^\sigma \left(\frac{W_t}{W_t^I}\right)^\sigma N_t.$$

Total wages are then given as

$$W_t = \left((\beta^F)^\sigma (1+\tau^N) {W_t^F}^{1-\sigma} + (\beta^I)^\sigma {W_t^I}^{1-\sigma}\right)^{\frac{1}{1-\sigma}}.$$

The wage bill is given as

$$WB_t^F = W_t \left(1 + \frac{T_t^N}{Y_t}\right) N_t^F,$$

$$WB_t^I = W_t N_t^I.$$

The share of informal labor in GDP is

$$s_t^{WB,I} = \frac{WB_t^I}{P_t^{FCST} Y_t}.$$

## 3.4 GDP: Income measure

GDP from the income side is the sum of the aggregate wage bill $(W_t N_t)$ and gross operating surplus $(R_t K_t)$. Adding net indirect taxes less subsidies closes the system:

$$Y_t^{CN} = W_t N_t + R_t K_t + NIT_t^{CN}$$

$$Y_t^{KN} = \frac{W_t N_t}{P_t^Y} + \frac{R_t K_t}{P_t^Y} + \frac{NIT_t^{CN}}{P_t^Y}$$

The representative agent determines her consumption based on income, prices and preferences and allocates the remainder to savings or borrows in the case where expenditures exceed incomes. Private sector borrowing may be derived either from domestic or external sources (capital inflows).

## 3.5 Fiscal accounts

### 3.5.1 Budget balance

The budget balance $(BB_t)$ is the difference between total revenues $(T_t^T)$ and expenditures $(G_t^T)$:

$$BB_t = T_t^T - G_t^T$$

### 3.5.2 Revenues

Total revenues $(T_t^T)$ are the sum of direct revenues $(T_t^{DRCT})$, value-added taxes $(T_t^{VAT})$, customs duties $(T_t^M)$, fossil fuel taxes $\left(T_t^{Fossil}\right)$ and electricity tariffs $\left(T_t^{Elec}\right)$ and other revenues $(T_t^{OTH})$:

$$T_t^T = T_t^{DRCT} + T_t^{VAT} + T_t^M + T_t^{Fossil} + T_t^{Elec} + T_t^{OTH}$$

Each revenue component equals its effective tax rate multiplied by the tax base:

$$T_t^i = \tau_t^i * TB_t^i$$

The tax base for direct taxes is the sum of the formal private and public sector wage bill and the gross operating surplus. The tax base for VAT is nominal household and government consumption while nominal imports are the tax base for customs revenues.

### 3.5.3 Expenditures

Government expenditures ($G_t^T$) equal the sum of use of goods and services ($G_t^{GS}$), compensation of employees ($G_t^{COE}$), net acquisition of non-financial assets ($G_t^I$), social expenditures ($G_t^{SOC}$) (e.g. transfers of the government to households), interest expenses ($G_t^{DSC}$) and others ($G_t^{OTH}$):

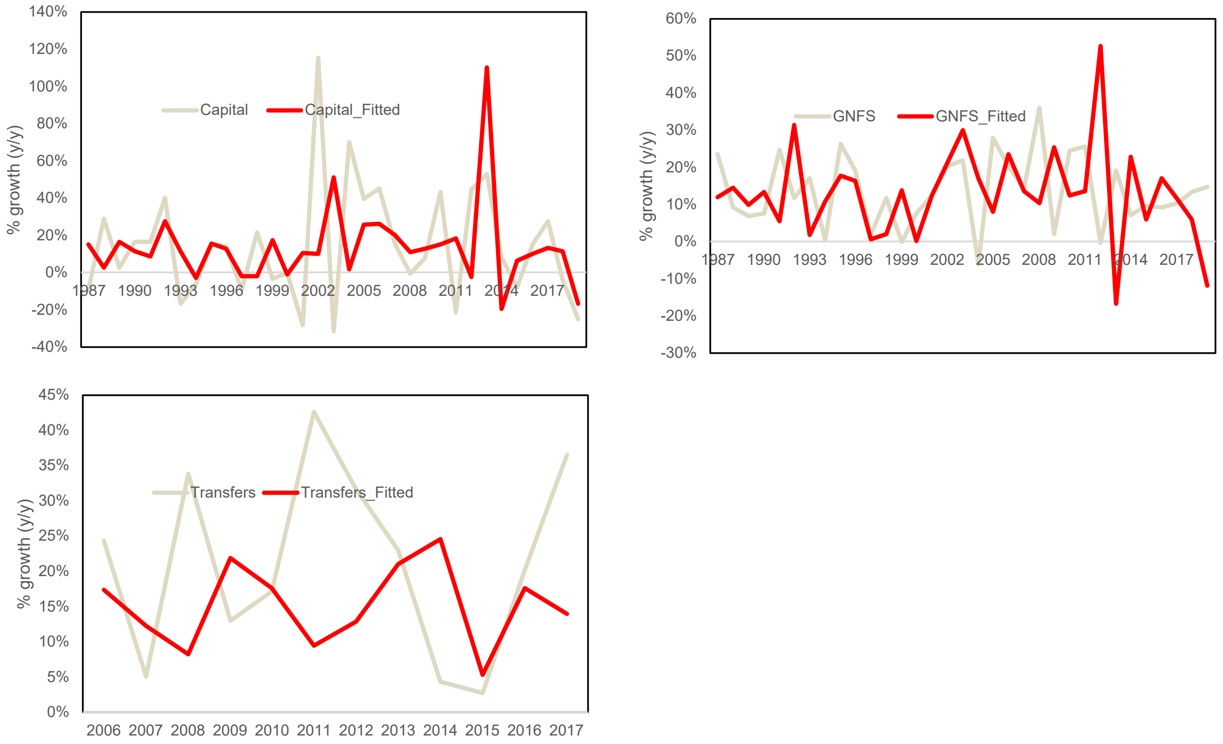
$$G_t^T = G_t^{GS} + G_t^{COE} + G_t^I + G_t^{SOC} + G_t^{DSC} + G_t^{OTH}$$

Expenditures are mostly discretionary since governments have full control over them. From a modeling perspective the choice either entails assuming explicit functional forms for expenditures or leaving them as exogenous. We follow the former by specifying a simple rule (which can be switched off in simulation mode). We assume that the government runs a structural deficit target equal to $BB_t^*$, which is assumed to equal -3%. Given that revenues are already determined, each expenditure component (except for interest payments) can be modeled as:

$$G_t^i = \alpha_i G_{t-1}^i + (1 - \alpha_i)\ [\theta_i(T_t - G_t^{DSC} - BB_t^*)]$$

where $\alpha_i$ measures the rigidity of expenditure $i$ and $\theta_i$ is the mean historical share of expenditure $i$ to revenues net of debt service costs where $\sum\theta_i = 1$. This ensures that the budget solves to the targeted budget in the long run. While Pakistan does not follow a fiscal rule, the above functional form does fit the reasonably well (Figure 5).

Figure 5: Fitted values of the fiscal rules

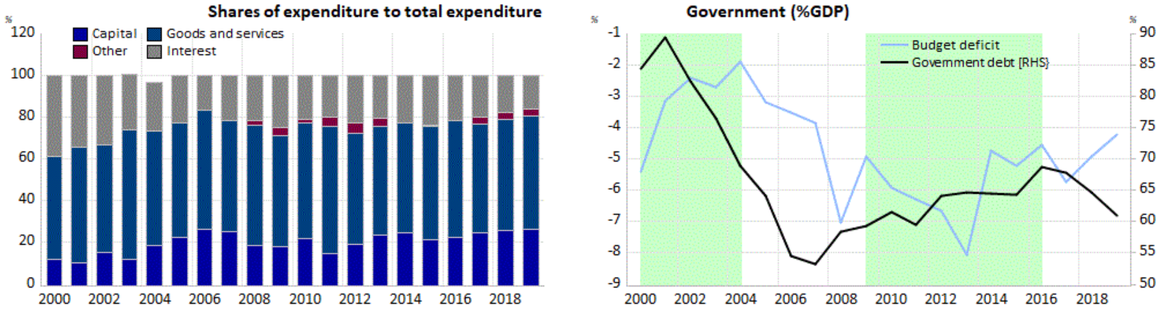


Source: Own calculations

The user has the option of turning the rule on, useful ensure fiscal sustainability, or to turn off the rule to allow the fiscal consequences under unchanged policies to be examined.

Historically purchases of goods and services and compensation of employees make up the largest share of total expenditure with a large component dedicated to servicing debt (see Figure 6).

Figure 6: Fiscal variables



Source: Macro Poverty Outlook and own calculations

## 3.6 The financial sector in PAKMod

PAKMod includes a highly simplified representation of the financial sector, comprised of four inter-related interest rates: (1) the natural rate of interest; (2) the monetary policy interest rate; (3) the cost of capital; (4) and the average rate of interest on government debt. The natural rate of interest feeds into the monetary policy rate.

In PAKMod, the natural rate is determined as a function of the marginal product of capital, while the monetary policy rate by a Taylor rule linking it to the natural rate, the output gap and the difference between expected inflation and the State Bank of Pakistan's inflation target. The cost of capital is determined by taxes on corporate incomes, the weighted average on government debt, rate of capital depreciation and a risk premium. The average interest rate paid on government debt is a weighted function of the interest rates on outstanding debt of different tenor. The monetary policy rate affects the average interest rate on government debt, while the term premium is a function of debt. Investment decisions rely on the return to capital vs. the user cost of capital. The return to capital depends on the productivity of capital.

The cost of capital comes is derived above when discussing investment decisions.

The policy rate is derived from a modified Taylor Rule, and is a function of inflation expectations deviations from target ($\pi_t^e - \bar{\pi}_t$) and the output gap ($Y_t^{gap}$). Note that when the output gap is zero and expected inflation is equal to target, then monetary policy interest rates equal the natural rate on interest (which equals the real natural rate plus the inflation target).

$$i_t^{MP} = \underbrace{r^n + \pi^*}_{i^n} + \theta(\pi_t^e - \pi^*) + \beta Y_t^{gap} + \varepsilon_t^i$$

The yield on outstanding government bonds (and the interest paid on newly emitted paper) of a given maturity should, at any moment, equal the weighted sum of the expected short-term interest rates (expectations hypothesis) and a liquidity premium:

$$i_t^k = \frac{1}{k} \sum_{j=1}^{k} i_{t+j}^{SR} + term_t^k$$

where $i_t^k$ is the yield of a *k* period bond.

These yields will determine the coupon rate of new issues, but they differ from the coupon rate of already issued paper – which is what determines the interest payments that the government needs to make on its debt. The average interest rate paid on outstanding government debt will be the face value of outstanding debt divided by a weighted average of all outstanding debts ($FV$) multiplied by their coupon rates ($i_t^F$) plus the discounted face value at maturity ($M_t$).

$$i_t^B = \sqrt[k]{\frac{FV_t}{\sum_{j=1}^{k}\left(\frac{FV_t * i_t^F}{(1+i_t)^j}\right) + \frac{M_t}{(1+i_t)^k}}} - 1$$

We do not model the different yields given data limitations on when bonds have been issued, their maturity structure and the coupon rates. Instead, we calculate the historic interest rate on government debt as the share of debt interest repayments to the previous stock of debt.

$$i_t^B = \frac{G_t^{DSC}}{D_{t-1}}$$

Our simplified equation for interest on newly issued debt is a function of the short-term interest rate and a premium ($term_t$):

$$\Delta i_t^B = \alpha + \theta(i_{t-1}^B - i_{t-1}^{MP}) + \beta_1 \Delta i_t^{MP} + \Delta term_t$$

The premium is modeled as an increasing function of debt above a threshold ($D^*$) (here assumed to be 60% of GDP):

$$term_t = \alpha + \beta * \left(e^{D_t - D^*} - 1\right),$$

This expression is important to ensure that Pakistan cannot run infinitely large public debt. When debt exceeds the threshold, the premium increases the bond interest rates. The higher bond interest rates increase the cost of capital, hence reducing investment.

We can map the nominal interest rates to real rates via the Fisher equation where real rates enter the household decision:

$$r_t^{SR} = i_t^{SR} - E_{t-1}\pi_t$$

$$r_t^B = i_t^B - E_{t-1}\pi_t$$

The yield curve is then the difference between the long and short-run interest rates:

$$r_t^{yield} = r_t^B - r_t^{SR}$$

To derive the natural rate of interest we start with the no-arbitrage condition, where the marginal product of capital should equal the cost of capital in steady state.:

$$MPK_t(1 - \tau_t^{CIT}) = P_t^I r_t^b + \delta P_t^I - \pi_t$$

Or in terms of the capital rental rate $R_t$:

$$\underbrace{(1-\alpha)\frac{P_t^Y Y_t^*}{K_t}}_{MPK}(1-\tau_t^{CIT}) = P_t^Y R_t(1-\tau_t^{CIT}) = P_t^I r_t^B + \delta P_t^I - \pi_t$$

Isolating in terms of the rental rate:

$$R_t = \frac{P_t^I}{P_t^Y}\frac{(r_t^B+\delta)-\pi_t}{(1-\tau_t^{CIT})}$$

Using the Taylor rule, in the long run when inflation equals its target and when GDP equals potential GDP, the monetary policy rate should equal the nominal natural rate $i_t^{MP} = i^n$.

Also noting that the average bond interest rate is equal to the monetary policy rate plus a spread (for now assume it is equal to zero) we can solve for the nominal natural rate of interest as:[14]

$$\left(\frac{P_t^I}{P_t^Y}\frac{[(i_t^{MP}+\delta)-\pi_t]}{(1-\tau_t^{CIT})}\right) = (1-\alpha)\frac{Y_t^*}{K_t} \to i^n = \frac{\left[P_t^Y(1-\tau_t^{CIT})\left[(1-\alpha)\frac{Y_t^*}{K_t}\right]\right]}{P_t^I} + \pi_t^{TRG} - \delta$$

This connects the marginal product of capital (net of depreciation and taxes) and the inflation target to monetary policy interest rates in the long run.

The management of the exchange rate is done via official reserves and the support of reserves via open market operations.

Since price stability is the target, we use a Taylor rule to model interest rate responses.

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[14] The Wicksellian *real* natural rate is: $r = \alpha\frac{n+\delta}{s} - \delta$, is similar, where $n+\delta$ can be thought of as the long-run growth of the economy and $s$ is the savings rate.

## 3.7 . The emissions module

The combustion of fossil fuels generates both carbon dioxide ($CO_2$) emissions and local air pollutants. PAKMod only tracks $CO_2$ emissions from the burning of hydrocarbons (coal, oil and natural gas). Other greenhouse gases are not tracked, nor are carbon emissions from biomass (see earlier discussion) or other sources.

### 3.7.1 Carbon emissions

The value-added each energy type is given by

$$Y_{k,t}^{CN} = Y_{k,t}^{KN} * P_{k,t}^{XN}.$$

The application of the scaling factor is reversed to get back to physical quantities.

$$\hat{Y}_{k,t}^{CN} = \frac{Y_{k,t}^{CN}}{\gamma^{CN}}.$$

The physical quantity is then obtained by dividing the value with the price,

$$Q_{k,t} = \frac{\hat{Y}_{k,t}^{Value}}{fx_t * P_{k,t}^{USD} * \beta^k + \tau^k * \alpha^k}.$$

Similarly, the quantities for imports are obtained,

$$Q_{k,t}^{M} = \frac{M_{k,t}^{CN}}{fx_t * P_{k,t}^{USD} * \beta^k + \tau^k * \alpha^k}.$$

Emissions per energy source is computed as the sum of energy production and imports (physical quantities) multiplied by the emissions factor. Total emissions are then simply the sum of all emissions by type.

$$EM_{k,t} = \left(Q_{k,t} + Q_{k,t}^{M}\right) * \alpha^k,$$

$$EM_{T,t} = \sum_i EM_{k,t}.$$

Revenues from carbon taxation (where negative revenues are expenses for fossil fuel subsidies) are calculated using the bilateral exchange rate, the sum of emissions (which are in dollars) multiplied by the subsidy/tax rate.

$$T_t^{Fossil} = fx_t * \left(\sum_k EM_{k,t} * \tau_t^k\right).$$

### 3.7.2 Air pollution

Local air pollutants are an important health threat. According to the World Health Organization (WHO), every year, 4.2 million people die from outdoor air pollution and an additional 3 million from indoor air pollution globally. Reducing local air pollutants is an important co-benefit of climate change mitigation (Rauner et al. 2020) and should be considered when assessing the net cost of climate policy. For example, the health benefits from reduced air pollution have been found to outweigh the cost of climate change mitigation in India (Markandya et al. 2009) and globally (Markandya et al. 2018).

With respect to local air pollutants, in PAKMod we concentrate on the most important air pollutant, particulate matter (PM 2.5). IIASA's GAINS model, provides a much more detailed modeling of air pollution (including from non-hydrocarbon sources), although without the fiscal and economic levers of the present model.[15]

### 3.7.3 Fuels and pollution level

$CO_2$ stays in the atmosphere for a long time and is decomposed only slowly over time. PM 2.5 by contrast does not accumulate in the atmosphere, because it settles to the ground a short time after emission. The concentration of PM 2.5 in the atmosphere thus strongly depends on recent emissions. Its harmfulness depends on wind patterns, the distance between emission sources and air quality within airsheds.[16] For example, it makes a difference, whether fuels are combusted in power plants, transportation, crop burning, construction or in waste burning.

While the $CO_2$ emissions per fuel is a fuel-specific but global constant, such a constant does not exist for local air pollution. We thus use the data from the Carbon Pricing Assessment Tool (CPAT), see (World Bank 2020b), which calculates country-specific values for the pollutant intensity of fuel combustion from very detailed data. Note that NOx and SO2 are precursors of PM2.5, that means NOx and SO2 are emitted when fuels are burned and then they become PM2.5 in the air (Fantke et al. 2017; Humbert et al. 2011). These data distinguish, for example for five different types of liquid fuels, between emissions in different sectors and whether pollutants are emitted at ground level or from stacks.

Table 2: Fuel consumption and pollution intensity in Pakistan

| Fuel | Fuel consumption in 2017 (ktoe) | Pollution (ug/m3 per ktoe) |
|---|---|---|
| **Coal** | 10,079 | 5.35E-05 |
| **Natural gas** | 26,155 | 2.96E-05 |
| **Oil** | 7,213 | 2.82E-04 |
| **Gasoline** | 8,037 | 3.31E-04 |
| **Diesel** | 9,539 | 4.38E-04 |
| **LPG & kerosene** | 1,508 | 3.05E-04 |
| **Jet fuel** | 115 | 2.93E-06 |

Source: for fuels: : (IEA 2021), for pollution: (World Bank 2020b)

Table 2 shows the fuel consumption for 2017 and the pollution intensity for Pakistan according to CPAT. We use the pollution intensity for coal and gas directly from the table. For the liquid fuels we take a weighted average, 3.53E-04 ug/m3 per ktoe. This is assigned to oil, which represents liquid fuels in the model.

The concentration of PM 2.5 pollution in Pakistan due to the domestic burning of fossil fuels in the year *t* is be calculated as

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[15] https://iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html

[16] Air pollution can be transported over long distances due to wind and cloud chemistry.

$$C_{PAK,t}^{PM2.5} = Coal_{PAK,t} * 5.35E^{-5}\frac{\frac{\mu g}{m^3}}{ktoe} + Gas_{PAK,t} * 2.96E^{-5}\frac{\frac{\mu g}{m^3}}{ktoe} + Oil_{PAK,t} * 3.53E^{-5}\frac{\frac{\mu g}{m^3}}{ktoe}$$

where $Coal_{PAK,t}$, $Gas_{PAK,t}$ and $Oil_{PAK,t}$ are coal, oil and gas consumed in Pakistan in year $t$, measured in ktoe. Notice that the total PM 2.5 pollution concentration in the country can be higher than tracked in the model due to additional emissions from natural sources, industrial processes other than combustion and pollution from foreign sources. Further, pollution concentration varies considerably within the country. The country-wide aggregation adopted from CPAT is a simplification, but a necessary one for a country model.

### 3.8 Damage module

Potential GDP is the supply potential of the economy and anchors the real side of the model. It determines how much output can be produced when all of the resource in the economy are fully employed (given existing distortions, technology and preferences). In PAKMod, the standard Cobb-Douglas specification for potential GDP ($Y_t^*$) is modified along five dimensions to accommodate the climate focus of the model:

1. Energy is included as a factor of production (see Hassler, Krussel and Olovsson, 2012);

and the production function is modified to account for damages from climate change, including:

2. Reductions in Aggregate TFP due to lower agricultural productivity
3. Reduction in labor productivity and supply due to higher temperatures
4. The impact of pollution on the labor force and
5. The impact of flooding on capital stock.

Before accounting for damages the standard MFMod production function is modified to include energy as a factor of production. In the revised form potential GDP is given as below, as a function of total factor productivity (TFP or ($A_t$)), capital stock ($K_t$), energy $\left(Y_{E,t}^{KN}\right)$ and structural employment ($N_t^*$).

$$Y_t^* = A_t K_t^{\alpha} N_t^{\beta} Y_{E,t}^{KN\,\gamma}$$

Where $\alpha$ is the income share of capital, $\beta$ is labor's share in total income and $\gamma$ is the share of energy, where the values of each of these parameters is drawn from the input-output table for Pakistan and set to 0.2, 0.7, and 0.1, respectively. $A_t$ represents total factor productivity, $K_t$ is productive capital and $N_t^*$ the equilibrium employment level and is determined as:

$$N_t^* = (1 - UNR_t^*)PR_t POP_t^{1564}$$

$UNR_t^*$ is the equilibrium unemployment rate, derived from a NAWRU (non-accelerating wage rate of unemployment) specification, $PR_t$ is the participation rate while $POP_t^{1564}$ is the working age population, which (like the total population) is exogenous and taken from the UN Population forecasts. The structural unemployment rate reflects various rigidities, which include a price and wage markup as well as an income tax wedge.

Potential output and the related notions of equilibrium labor demand and equilibrium wages and prices are central to the adjustment process. When quantities demanded of goods and factors of production are above or below their equilibrium values, prices will rise (fall) to help re-equilibrate the economy.

To find the equilibrium labor and capital demands, the representative firm minimizes the costs of labor and capital ($P_t^{fcst} Y_t^{KN} = R_t K_t + W_t N_t + P_{E,t}^{XN} Y_{E,t}^{KN}$) subject to the production function. The first order conditions are:

$$K: R_t = \alpha \frac{(P_t^{fcst} Y_t^{KN})}{K_t}$$

$$N: W_t = \beta \frac{P_t^{fcst} Y_t^{KN}}{N_t}$$

$$Y_{E,t}^{KN}: P_{E,t}^{XN} = \gamma \frac{P_t^{fcst} Y_t^{KN}}{Y_{E,t}^{KN}}$$

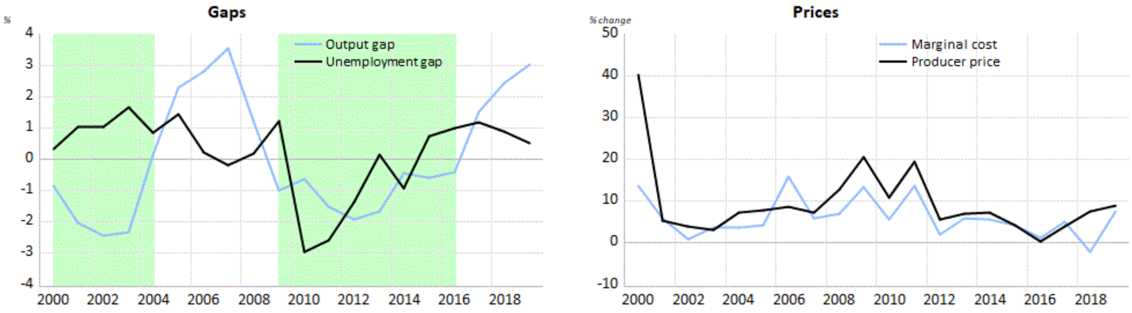
The nominal marginal costs are calculated using the first order conditions and the production function:

$$MC_t = \left(\frac{1}{A_t}\right)\left(\frac{R_t}{\alpha}\right)^{\alpha}\left(\frac{W_t}{\beta}\right)^{\beta}\left(\frac{P_{E,t}^{XN}}{\gamma}\right)^{\gamma}$$

Marginal cost is a weighted average between labor, energy and capital costs and decreases with TFP.

Figure 7 plots the historical relationship of these variables. The left panel shows the output gap and the unemployment gap are mostly asynchronous for all period except between 2010-2018. Factor prices and nominal marginal costs move stepwise.

Figure 7: Gaps and prices



Source: Macro Poverty Outlook and own calculations

### 3.8.1 Components of the damage module

PAKMod incorporates five main channels by which the climate and environmental outcomes impact the economy: 1) Pollution impacts on human health and labor productivity; 2) pollution impacts on human mortality; 3) Damages to labor productivity from higher temperatures; 4) Damages to agricultural productivity due to higher productivity; and 5) Damages to the capital stock from extreme climate events.

### 3.8.2 Damages due to pollution: Working days lost

According to Ostro (1987), working days lost attributable to pollution ($WDL_{pollution}$) can be calculated as

$$WDL_{pollution,t} = Pop_{PAK,t}^{15to64} * Per\ person\ WDL_{baseline} * \left(1 - \exp\left(-0.0046 * C_{PAK,t}^{PM2.5}\right)\right).$$

Where $Pop_{PAK,t}^{15to64}$ is the population between ages 15 and 64.

Unfortunately, there are no estimate for the baseline of working days lost due to illness per person, $Per\ person\ WDL_{baseline}$, for Pakistan. We approximate this value by taking the average of countries at a similar level of development, notably Moldova, Ukraine and Uzbekistan three lower middle-income countries. See Table 3. for the calculation of the WHO adjusted value.

The methodology to estimate the health impacts of air pollution is based in (GBD 2017 Risk Factor Collaborators, 2018), which estimates jointly the effects of indoor and outdoor air pollution. For further details, please refer to (World Bank 2020b). The methodology to estimate changes in air pollution is based, among others, (Y. Zhou et al. 2006; Humbert et al. 2011; Fantke et al. 2017; GBD 2017 Risk Factor Collaborators 2018), for further details, please refer to (World Bank 2020b).

Table 3: Lower-middle income countries with data on working days lost due to illness

| Country name | WHO - Days per employee | Employment to population ratio, 15+, (%) | WHO adjusted (Days per person) |
|---|---:|---:|---:|
| **Uzbekistan** | 10.4 | 62.1 | 6.4584 |
| **Moldova** | 7 | 40.6 | 2.842 |
| **Ukraine** | 3.7 | 48.9 | 1.8093 |
| **Average** | | | **3.7** |

Source: WHO (2019) and (ILO 2020)

### 3.8.3 Damages due to pollution: Cause of death

The number of deaths which can attributed to local air pollution can is expressed as a linear function, where deaths due to air pollution are additional to working days lost. We write the number of deaths which can be attributed to local air pollution as

$$Deaths_{PAK,t}^{PM2.5} = deaths\ per \frac{\mu g}{m^3} per\ person * Pop_{PAK,t} * \left(C_{PAK,t}^{PM2.5} - tmrel\right).$$

The population in Pakistan in year $t$, $Pop_{PAK,t}$ is an exogenous variable derived from UN population projections, while pollution concentration, $C_{PAK,t}^{PM2.5}$, (expressed as $\frac{\mu g}{m^3}$) is derived endogenously as a function of economic activity (see below). The theoretical minimum risk exposure level, $tmrel$, for PM 2.5 is assumed to be uniformly distributed between 2.4 and 5.9 so that $tmrel = \frac{5.9+2.4}{2} = 4.15$ (GBD 2017 Risk Factor Collaborators 2018, Supplementary Appendix, page 73). We use $deaths\ per \frac{\mu g}{m3} per\ person$ as a parameter and calibrated to equal $.80E-06$ based on data from the year 2017.

The parameter value is calculated as follows. First Estimates of urban and rural deaths from air pollution for Pakistan were extracted from (World Bank 2020b) as $total\ AP\ deaths_{rural} = 56{,}205$ and $total\ AP\ deaths_{urban} = 34{,}078$. These were combined with WHO (1987) estimates for average pollution concentrations in urban ($PM2.5_{urban} = 56$) and rural areas ($PM2.5_{rural} = 52$) . These were then combined with population data to derive deaths per unit of PM2.5 as

$$deaths\ per \frac{\mu g}{m3} per\ person = \frac{urban\ deaths\ per \frac{\mu g}{m3} + rural\ deaths\ per \frac{\mu g}{m3}}{Pop_{PAK,2017}},$$

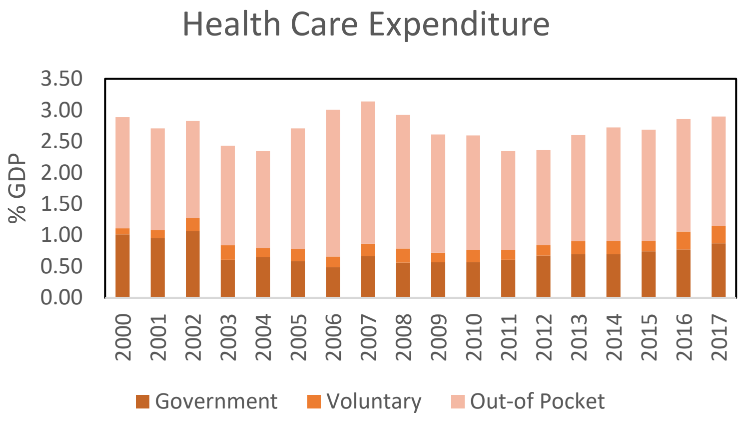
The economic value of life is not calculated in the model. Instead we only report deaths related to pollution.

#### 3.8.3.1 Health expenditure attributable to pollution

Health expenditure due to pollution was estimated following the methodologies described in Preker *et al.* (2016); WHO (2020) and elaborated in World Bank (2020). Note that in the model medical costs are not a deadweight loss as the correspond to a redistribution of resources from households to the health care sector.

The first step uses WHO (2020) estimates of total health care expenditure as share of GDP in 2017 (for which data is available), which was 2.9% ($THE_{PAK,2017}$) or 762.8m rupees.

Figure 8: Health care spending by payee as a percent of GDP.



Source: WHO (2020)

The second step determines the share of health expenditure attributable to pollution. For this step data on the disability adjusted life years (DALY),[17] for each disease "d" associated with air pollution (chronic obstructive pulmonary disease, lower respiratory infections, stroke, diabetes mellitus type 2, ischemic heart disease, tracheal, bronchus, and lung cancer), is divided by total disability adjusted life years in each year and then multiplied by the proportion of the population with disease d.

$$\sum_d \frac{DALYs_{d,c,2017}}{TotalDALYs_{c,2017}}$$

In the model nominal spending on health care is assumed to rise linearly in line with GDP and the increase in the concentration of 2.5mm particles in excess of the previously discussed threshold level.

Thus, health expenditure due to pollution in year t is given by

$$HEAP_{PAK,t} = HEAP_{PAK,2017} * \frac{GDP_{PAK,t}}{GDP_{PAK,2017}} * \frac{C_{PAK,t}^{PM2.5} - tmrel}{C_{PAK,2017}^{PM2.5} - tmrel}.$$

The 2017 HEAP value is calculated as

$$HEAP_{PAK,2017} = GDP_{PAK,2017} * THE_{PAK,2017} * \sum_d \frac{DALYs_{d,c,2017}}{TotalDALYs_{c,2017}} * PAF_{d,2017}.$$

$DALYs_{d,c,t}$ are disability adjusted life years, for disease d, country c, year t and $TotalDALYs_{c,2017} = \sum_d DALYs_{d,c,2017}$. $PAF_{d,t}$ (population attributable fraction) represents the share of all people suffering from the disease $d$ in year $t$, that contracted it because of pollution.[18] Data for the PAF are sourced from the CPAT model (World Bank 2020b).

### 3.8.3.2 Mapping working days lost to economic outcomes

Pollution impacts the economy on the one hand by reducing the labor force due to pollution-related deaths, and reducing total labor supply (measured in hours worked) by the hours lost by those workers who suffer from pollution related disease but do not die.

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[17] The disability-adjusted life year, $DALY$, is a summary measure which combines time lost through premature death and time lived in states of less than optimal health or "disability". DALY, for a specific cause $c$, sex $s$, age $a$ and year $t$ is defined as:

$$DALY_{c,s,a,t} = YLL_{c,s,a,t} + YLD_{c,s,a,t},$$

where YLL are years of life lost and YLD are years lived with disease. The values for $DALYs$, $YLL$ and $YLD$ are obtained from the GBD results tool (IHME 2018).

[18] The population attributable fraction ($PAF$), is the reduction in incidence that would be observed if the population were entirely unexposed, compared with its current exposure pattern. $PAF$ for each mortality type $c$ and age range $a$ is calculated as

$$PAF_{c,a} = \frac{\sum_{i=1}^{n} P_{i,a} * \left(RR_{c,a} - 1\right)}{\sum_{i=1}^{n} P_{i,a} * \left(RR_{c,a} - 1\right) + 1},$$

where $RR_{c,a}$ is the relative risk for cause $c$ and age group $a$ and $P_i$ is the percentage of the population exposed to level of pollution $i$.

#### *Reduction in effective labor supply due to reduced hours worked*

As discussed above labor force ($LF_t$) in Pakistan depends on the participation rate ($PR_t$) and the working age population ($Pop_t^{15+}$).

$$LF_t = PR_t * POP_t^{1564},$$

To account for reduced working days we introduce the notion of effective labor force and substitute this notion for the labor force in the standard MFMod system, where the effective labor force, $\widehat{LF}_t$ is equal to the product of the normal labor force and the ratio of days of work lost to pollution/ divided by total working days (assumed to be 240).

$$\widehat{LF}_t \; = LF_t * \left(1 - \frac{WDL_{pollution,t}}{WD_t}\right).$$

The equation above will modify structural employment and hence potential GDP:

$$Y_t^* = A_t K_t^{\alpha} \left[(1 - UNR_t^*)\widehat{LF}_t\right]^{\beta} Y_{E,t}^{KN^{\gamma}}$$

#### *Reduction in effective labor supply due to premature death*

Calculating the macroeconomic impact of a death due to air pollution is more difficult to quantify. World Bank (2020c) provides an age distribution of deaths due to air pollution. With this, we could estimate the number of working years lost due to workers dying prematurely from air pollution. This could then be used to estimate the reduction in GDP.

We could consider the effect of death due to air pollution on GDP per capita. Note that a death reduces not only labor supply, but also the denominator, population size. The death of a retired person would increase GDP per capita. According to World Bank (2020), 57.7% of deaths due to air pollution occur in persons older than 60 years. This means that air pollution deaths can be expected to increase GDP per capita. Notice that this difficulty does not occur for working days lost as sickness caused by air pollution does affect labor supply, and hence GDP, but not the population size. We report deaths due to air pollution separately.

#### *Fiscal implications of pollution-related disease*

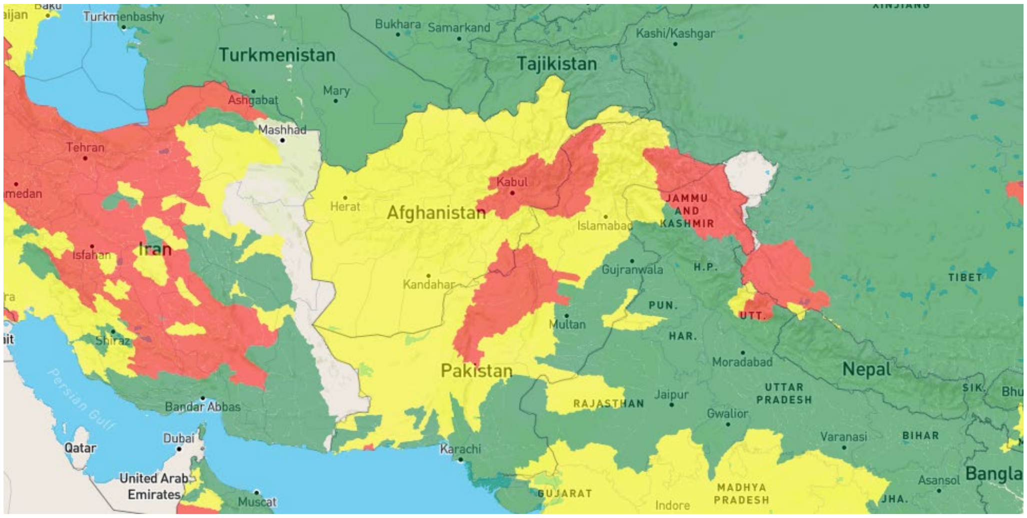
Data show that about 60% of health care expenditure in Pakistan is financed out of pocket while the remainder is effectively financed from the government. In the modeling we assume that these shares are constant so that government's share of health care expenditures is given by $(1 - \Theta)HEAP_{PAK,t}$ where $\Theta$ is the share of health care expenditures financed by households and is set to 0.6. and this amount is included in the government goods and services expenditure equation.

### 3.8.4 Damages to agricultural productivity

While Pakistan's mitigation impacts on agricultural damages are negligible, the costs of these given damages are not necessarily small. There is a vast literature on the impact of climate change on agricultural productivity. In an influential study, Schlenker and Roberts (2009) show a strong nonlinearity in crop yields. Yields for corn, soybeans and cotton increase in temperature until temperatures reach around 30°C. Beyond that productivity declines sharply. In a very comprehensive and systematic assessment of the effect of climate change on agricultural production, Rosenzweig *et al.* (2014) find strongly negative effects of climate change. Similar results and further details are provided in Zhao *et al.* (2017) and Scheelbeek *et al.* (2018).

Figure 9 illustrates the risk of drought in Pakistan as one contributor to a reduction in agricultural productivity. The figure shows the change in a drought indicator for the year 2050. The green area indicates a low amount of change (more than -5%), the yellow area a medium change (between -5% and -15%) and the red area a high change (less than -15%).

Figure 9: Map of a drought indicator for Pakistan.



Source: Climate Change Knowledge Portal

*Data*

Information on agricultural output losses was informed by background data generously shared by Leclère *et al.* (2014) and Havlík *et al.* (2015). The data were derived from various models and scenarios.[19] Farmers are constantly internalizing and adapting to climate change in their production methods, and this is expected to continue as climate change progresses. These adaptation measures include crop substitution, irrigation, changes in planting dates and area expansion (Nelson et al. 2014).

Table 4 reports the yield loss which would occur without farmer adaptation (Total impact), the reduction that farmer optimization behavior can be expected to generate in those losses (Private adaptation effect) and the difference between the two (the net effect). The data is sourced from a regional study (not Pakistan specific), and for the aggregate effect across all crops (variable "CRP"), the average of the global circulation models (GCM) and the policy "NoMitig". The data is available for two of the Shared Socioeconomic Pathways (SSPs) proposed in Riahi *et al.* (2017), SSP 4 and SSP 5. The climate damages are

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[19] Data used were from the "production" sheet in the Excel file named "CC_MTG_impacts_15apr15_wDM_v2.xlsx", because this sheet contains the data on the losses in agricultural production (the sheets "Climate shock" and "Yield" contain the same data).

similar in the two SSPs. Given current mitigation efforts we choose to work with SSP 5 ("Taking the Highway"). With these scenario choices, we obtain Table 4.

Table 4: Agricultural losses in South Asia

| | **RCP 2.6** | | | **RCP 8.5** | | |
|---|---|---|---|---|---|---|
| | Net impact | Direct impact | Private Adaptation effect | Net impact | Direct impact | Private Adaptation effect |
| **2000** | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| **2010** | -1.26% | -2.29% | 1.03% | -0.77% | -1.46% | 0.69% |
| **2030** | -1.73% | -3.68% | 1.95% | -2.29% | -5.25% | 2.96% |
| **2050** | -1.17% | -2.30% | 1.13% | -4.93% | -10.08% | 5.15% |
| **2080** | -1.74% | -3.35% | 1.61% | -14.73% | -22.66% | 7.93% |

Source: (Havlík et al. 2015)

In the model, we will work with the numbers for the net impact, because the private adaptation is reported in the table is effectively the kind of optimization behavior embedded in the model. For the intermediate years, we interpolate linearly.

*Model modifications*

In order to account for climate damages ($D_t$) to agricultural output (note that it has a negative sign), we include it explicitly in the calculation of value added in the agricultural sector:

$$\Delta \log (Y_{AGR,t}^{KN}) = c_1 - \theta^{AGR} * \log (Y_{AGR,t-1}^{KN}) - \log ((1 + D_{t-1}) * \hat{Y}_{AGR,t-1}^{KN})) + \Delta \log ((1 + D_t) * \hat{Y}_{AGR,t}^{KN})$$

This equation derives value added for the crop sector, a sub-sector of agriculture, from the value in the social accounting matrix (SAM). $D_t$ reflects the damages caused by climate change in year $t$.

Potential GDP is not modeled bottom up from sectoral values. Instead potential GDP is calculated from the aggregate production factors. The agricultural damage has the effect of reducing TFP, because the same amount of capital and labor produces a reduced amount of output compared to previous years. The modification to potential GDP $Y_t^*$ is

$$Y_t^* = (1 + D * \omega_{AGR}^{Y}) A_t {N_t^*}^{\alpha} K_{t-1}^{\beta} {Y_{E,t}^{KN}}^{\gamma}$$

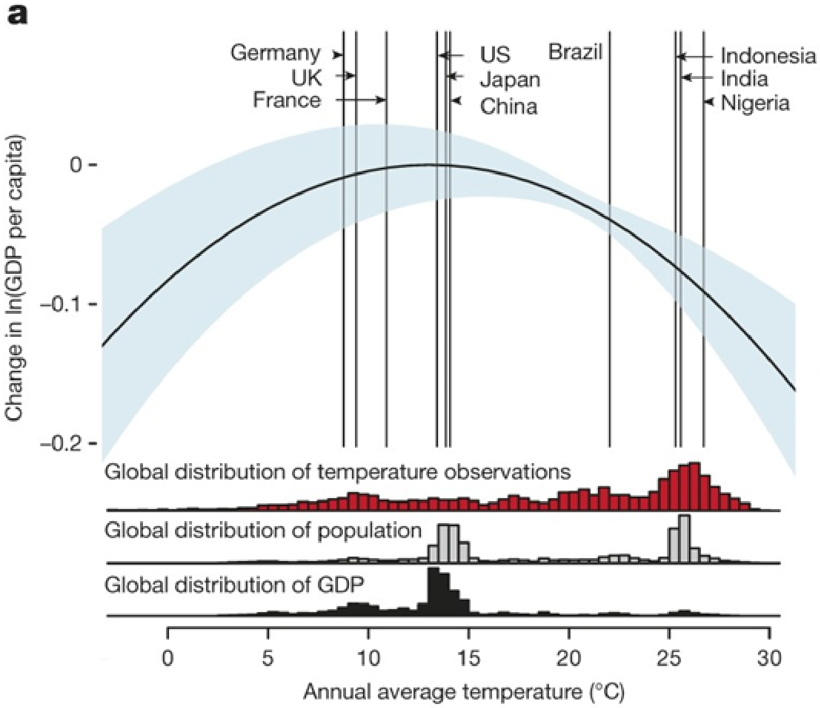
where $\omega_{AGR}^{Y}$ is the weight of agriculture in total value-added. It would have been ideal to map damages in the agricultural sector to changes in informal employment and wages, since they are most likely to be affected.

### 3.8.5 Heat impacts on labor productivity

There is extensive evidence that labor productivity is sensitive to temperature and that most countries are beyond the optimum, so that further temperature increases will reduce labor productivity (Burke, Hsiang, and Miguel 2015). According to Sherwood and Huber (2010 and Buzan and Huber (2020), there is an upper limit for humans to adapt to higher temperatures and at strong climate change many world regions would become uninhabitable. Firm level studies in India (Somanathan et al. 2018; Adhvaryuy, Kalaz, and Nyshadham 2019) and China (Zhang et al. 2018) show that heat reduces worker productivity.

Figure 10, reproduced from Burke, Hsiang and Miguel (2015), illustrates that the countries to the left of the peak stand to gain productivity from temperature increase and countries with already high average temperature (to the right) will experience a decrease in productivity. As Pakistan is expected to lose productivity, we model it explicitly.

Figure 10: The effect of temperature on GDP per capita



Source: Burke, Hsiang and Miguel (2015)

*Data*

Data for the loss in labor productivity at a national level in Pakistan are available in UNDP (2016) Table 1 and Roson and Sartori (2016).[20] We make use of the first of these, which is based on High Occupational Temperature Health and Productivity Suppression (Hothaps) project, and uses the well understood RCP scenarios.

UNDP (2016) provides estimates of working hours lost from 1995 to 2085 under the climate scenario RCP 2.6 and 8.5 (columns 1 and 2 of Table 5[21]). As current labor productivity in 2015 already includes the losses 4.1-4.7 percent recorded for 2015, we calculate the additional changes to hours worked from there onwards (columns 3 and 4), and these are the data introduced into the model to reflect impacts on labor

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[20] We do not use the data of (Burke, Hsiang, and Miguel 2015) as they are not available in the form we need.

[21] In percent. (UNDP 2016) does not provide direct data for RCP 2.6. The value is assumed based on the effect of a 0.5°C temperature increase in RCP 8.5 between 2015 and 2025.

productivity under RCP 2.6 and 8.5 respectively. Years between the dates in the table are estimated via linear interpolation.

Table 5: Labor productivity lost due to heat in RCP 8.5, in percent

| | Work hours lost | | Change as compared with 2015 | |
|---|---|---|---|---|
| **Year** | RCP 2.6 | RCP 8.5[22] | RCP2.6 | RCP8.5 |
| **1995** | | 3.73 | -0.67 | 0.67 |
| **2015** | | 4.1-4.7 | 0 | 0 |
| **2025** | | 5.22 | 0 | .82 |
| **2055** | | 7.00 | .92 | 2.6 |
| **2085** | | 9.97 | 0.82 | 5.57 |

These estimates give a good indication for the order of magnitude of heat stress on labor productivity, but do not include other factors like how heat will interact with air pollution, and changes in demographics (see below).

*Model modifications*

Potential GDP is modified once more, but now accounting for labor productivity losses due to heat. In order to capture the loss in labor productivity, we distinguish between work hours $L$ and effective work hours $\hat{L} = (1-h)L$, where $h$ is the percentage loss of hours given in the second data column in Table 5.

We implement this by modifying the equation for potential GDP to

$$Y_t^* = (1 + D * \omega_{AGR}^Y) A_t \big((1-h_t) N_t^*\big)^\alpha K_{t-1}^\beta {Y_{E,t}^{KN}}^\gamma,$$

where $A_t$ is trend TFP, $N_t^*$ is structural employment and $\omega_{AGR}^Y$ is the share of agriculture in GDP. The first part, $1 + D * \omega_{AGR}^Y$, was discussed above in the agricultural damages section.

### 3.8.6 Damages to physical capital from flooding

Pakistan is already affected strongly by flooding. Serious floods caused extensive damage in almost every year between 1985 and 2018 (Figure 11), with between one thousand and 20 million people being affected annually. Further data on the World Bank's Climate Change Knowledge Platform shows that between 1900 and 2018, a total of 93 flood events were recorded in Pakistan, which is equivalent to 45% of all natural-hazard events in Pakistan in that time interval.

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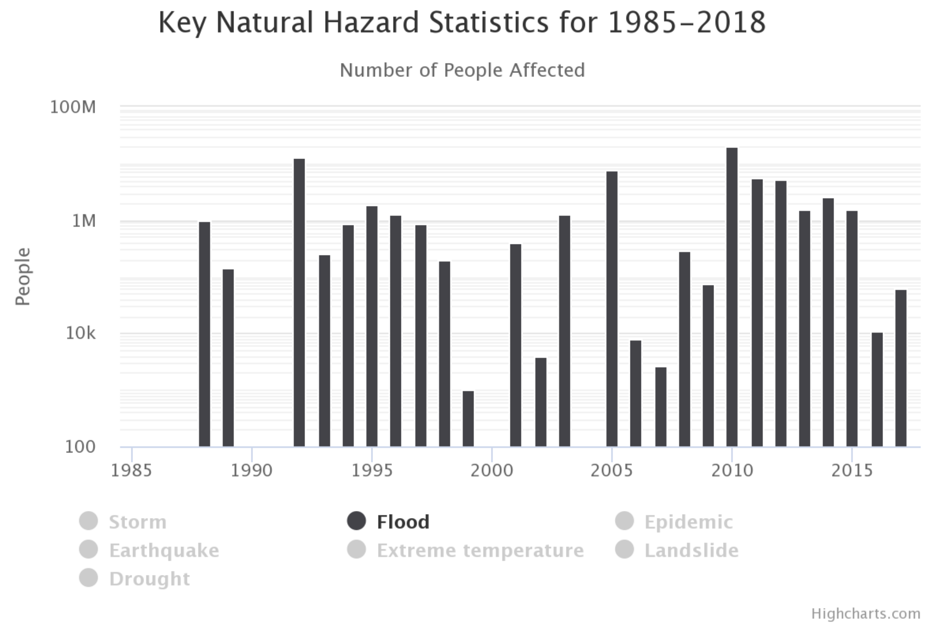
[22] Full description: "Potential annual daylight work hours lost for work at 300W, %; based on a business as usual scenario (RCP 8.5, average of HADGEM2 and GFDL models) current (1995) and up to 2085", see UNDP (2016).

Figure 11: People affected by floods in Pakistan



Source: Climate Change Knowledge Platform, World Bank

With climate change, the frequency of flooding is expected to increase (van der Schrier et al. 2018). We use current data on damages and frequency from UNISDR (2015)[23] and assume that the frequency of floods of any given size double with every degree increase in temperature (as suggested in Myhre *et al.* (2019)):

$$F(T) = 2^{T-T_0} * F_0,$$

where $F$ is the frequency of the event, $T$ is the temperature and a zero in the index marks the historical frequency.

For the conversion from RCP scenarios to temperature, we use Table 7. The first column of Table 6 reports the expected damage to the capital stock arising from floods of increasing severity. Column 2 shows the probability of each of those events under a 1°C of warming scenario based on the data of UNISDR (2015). The columns for 2°C of warming and 3.7°C of warming show the increased probabilities based on the above formula.

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[23] The data is available online here in a file named “GAR15 results feb 2016_PML mundo.csv”.

Table 6: Current and estimated probabilities for flood damages of a given size

| Damage | 1°C of warming | 2°C of warming | 3.7°C of warming |
|---:|---:|---:|---:|
| **0** | 91.233% | 82.467% | 43.034% |
| **1.04%** | 5.000% | 10.000% | 32.490% |
| **1.69%** | 2.000% | 4.000% | 12.996% |
| **2.17%** | 1.000% | 2.000% | 6.498% |
| **2.78%** | 0.400% | 0.800% | 2.599% |
| **3.02%** | 0.200% | 0.400% | 1.300% |
| **3.49%** | 0.100% | 0.200% | 0.650% |
| **3.65%** | 0.067% | 0.133% | 0.433% |

Source: UNISDR (2015), Myhre et al. (2019) and author's calculations

*Model modifications*

Damages are given in terms of the reconstruction cost of the damaged capital. For example, if a flood destroys a bridge and the reconstruction cost of the bridge is 10 million USD, then the official damaged caused by the destruction of the bridge is 10 million USD. However, the economic damage caused by the destruction of that bridge might be far higher than 10 million USD (Hallegatte & Vogt-Schilb, 2016) because the productivity of existing capital is higher than the productivity of marginal capital, which determines the replacement cost of existing projects.[24]

To accommodate this reality, the modeling must evaluate the productivity of investment to replace damaged capital goods differently from the productivity of new investment at the margin. In the model, it is assumed that the productivity of damaged capital is equal to the average productivity of capital. This is equivalent to assuming that the productivity distribution of damaged capital is the same as the productivity distribution of the existing capital stock or assuming the projects damaged are randomly selected from the total capital stock.

### 3.8.7 Tracking unrepaired damages

As modeled, capital destroyed by a flood has average capital productivity, while newly constructed capital has marginal productivity. In the modeling we distinguish between two types of capital: damaged capital $DS_t$ and normal capital $K_t$. The economic impact of a unit of damaged capital is equal to the average productivity of capital times the damaged capital $\frac{Y}{K} * DS_t$. The level of damaged capital at time $t$ and is determined according to the following formula

$$DS_t = DS_{t-1} + D_t - I_t^R,$$

where $D_t$ is new damage in time $t$, $DS_t$ is the stock of unrepaired damage and $I_t^R$ is investment into repairing damage. Note that this form keeps the memory of the capital stock that would have depreciated if was not destroyed.

In the modeling the amount of total investment $I_t$ the government can undertake is determined by the fiscal rule. Given that the capital destroyed by floods has an average capital productivity, it would be optimal to direct all investment to reconstruction. However, only a share of total government investment

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[24] This is a natural outcome of diminishing marginal productivity, which implies that average productivity of existing capital is greater than the productivity of new investments.

is typically allocated to replacing damaged capital, partly because damaged capital tends to be located in a small geographic area and investment priorities in other geographic and sub-national areas continue to be taken out, and because the required machinery (or skills) for reconstruction are not always available. To reflect these practical realities the model assumes that reconstruction investment cannot exceed a share $\varphi$ of total investment.

$$I_t^R = \min\{DS_t, \varphi I_t\}.$$

where for the purposes of this paper $\varphi = 0.5$.

To accommodate the idea that the economic impact of damaged capital exceeds that of marginal capital, potential output is modified once more to explicitly account for the higher productivity of destroyed capital. Thus

$$Y_t^* = (1 + D * \omega_{AGR}^Y) A_t \left((1 - h_t) N_t^*\right)^\alpha K_{t-1}^\beta Y_{E,t}^{KN^\gamma} - \frac{Y}{K} DS_t$$

Where the final term reflects the lost output from the (time variant) damaged capital, and $K$ reflects the sum of undamaged capital and damaged capital. Thus when $DS_t = 0$ the equation reverts to the standard potential output equation inclusive of other damages. Note that the treatment of damages is based on aggregate capital. Without distinct forms of capital, the assumption that destroyed capital has an average capital productivity might be underestimated in the case when destroyed key infrastructure renders labor and other capital unutilized. It might over-estimate the productivity effect when capital in the "middle of nowhere" is destroyed.

## 3.9 Adaptation module

PAKMod also includes logic to capture the impacts of adaptation investment to reduce the damages from climate events. Examples include storm proofing roads so they do not get damaged during floods, providing air-conditioning or emergency air-conditioned shelters to reduce the health and productivity impacts of heat waves, strengthening irrigation and drainage systems to limit the impacts of droughts and excess rainfall on agricultural output, and building sea walls to hold back rising oceans.

While evaluating the costs of adaptation investments is easy (assuming they are recorded in a budget tagging exercise), much less is known about the benefits they will generate. Adaptation is mostly analyzed at a project level and hardly ever quantified. Nor are the trade-offs accounted for, what other investments and benefits from investment did not get made in order to pay for an adaptation investment

In PAKMod we do not consider private-sector adaptation: adaptation that is undertaken by individuals recognizing that climate change has modified or will change the private return from a given activity. Such private-sector adaptation is undertaken when the private returns from the investment will equal or exceed the costs of undertaking it. In agriculture this might include things like changing crops to more drought resistant varieties[25] or purchasing (or paying more for) crop insurance. In the manufacturing sector, it could mean air-conditioning a shop floor because the loss in productivity of not air-conditioning would exceed the cost of providing the air conditioning. These kinds of substitution will

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[25] Indeed, in the damages discussion we netted out such savings from endogenous adaptation behavior when calculating the losses associated with higher temperatures in agriculture.

occur naturally in line with price signals through the standard mechanisms of the model. The kinds of adaptation investment covered here are ones undertaken by the public sector because the social gains of the investment exceed the social costs, and might include building a dyke around a community which would cost much less than each household providing individual protection, or hardening a roadway so that it did not wash out interrupting commerce between two cities. For additional literature regarding different types of adaptation see Appendix 3A.

### Introducing adaptation into PAKMod

To accurately model the economic consequences of adaptation we need to link spending on adaptation to the amount of damages avoided at a national level. Unfortunately there is little literature outlining the effectiveness of adaptation, indeed, we found only one source relating spending on adaptation to avoided damages (Multi-hazard Mitigation Council 2019).[26] The report refers only to investments in buildings in the United States, however.

Given the lack of direct data, a more speculative approach was taken constructing a protection function that linked spending on adaptation to damage avoided in a flexible fashion, such that parameters can be refined as more information becomes available. The approach here follows that of de Bruin, Dellink and Tol (2009) and De Cian *et al.* (2016). As with Lecocq and Shalizi (2007), de Bruin, Dellink and Tol (2009) Bosello, Carraro and De Cian (2010), and Millner and Dietz (2015), we assume that the product of adaptation investment is adaptation capital[27] that capital does not have a productive use. Adaptation capital works only to reduce damages. It is further assumed that a country that adapts, will implement the projects that offer the most protection per unit of expenditure first, and that subsequent adaptations will generate less protection (decreasing returns).

As discussed earlier in PAKMod total public investment is split into adaptation investment ($I^A$) and productive investment ($I^{GP}$ ) and the stock of adaptation ($K_t^A$) and productive capital ($K_t$) are tracked separately. Adaptation capital protects the economy from climate-related damage to productive capital (say flooding). The more adaptation capital an economy accumulates the less productive capital will be damaged by natural disasters. If a road is constructed in a resilient manner (perhaps larger and more frequent culverts to reduce the likelihood of washout), the cost of the road beyond the standard cost is not considered as productive and is treated as an investment in the adaptation capital stock. From a societal point of view adaptation investment makes sense if the productive capital saved (protected) by the investments exceeds the amount of investment forgone in order to make the adaptation investment.

The level of adaptation capital $K_t^A$ accumulates in the same way as productive capital and is assumed to have the same rate of depreciation, $\delta$, as productive capital.

$$K_t^A = (1-\delta)K_{t-1}^A + I_t^A.$$

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[26] (World Bank 2010) attempts calculate the costs of different adaptation investments, but there is limited information on how much protection (damage forgone) different investments yield. The (Multi-hazard Mitigation Council 2019) estimates the ratio between the cost of adapting buildings to natural disasters and the damages avoided with these investments. The organization finds that 11 dollars can be saved for 1 dollar invested in the case of applying international building codes. However, these data are estimated for the Unites States and apply to natural disasters generally, without explicit links to climate change. The results are thus not easily transferable to climate change adaptation in Pakistan.

[27] (Bosello, Carraro, and De Cian 2010), by contrast, use a flow variable for adaptation albeit in a model framework where a period is 10 years long.

We define the amount of adaptation capital that would be obtained if the government invests the equivalent of the annual expected climate damage from the source being protected as $K^{Amax}$. This is considered a maximum because if the government alternatively invested this amount in productive capital, then it would be able to replace the damaged capital directly at the same cost as doing the adaptation (assuming $1 of investment generated 1$ reduction in capital destruction).

If expected damages rise proportionately with GDP, then $K^{Amax}$ will rise in step with GDP and therefore $K_t^{Amax} = (1+g)K_{t-1}^{Amax}$, where *g* is the rate of growth GDP.

Inserting this in the equation for the accumulation of adaptation capital, and substituting expected Gross Damages $\overline{GD}_t$ for $I^A$ gives the

$$K^{Amax} = \frac{1+g}{g+\delta}\overline{GD}.$$

Not all adaptation capital projects will offer the same level of protection per unit of adaptation capital. To account for this, we assume a declining marginal increase in protection in line with the literature (de Bruin, Dellink, and Tol 2009). The amount of protection, $P$, from a given level of adaptation capital $K^A$ can then be expressed as a function of the ratio of actual investment $K^A$ and the maximum adaptation capital stock,

$$P = \gamma_1\left(\frac{K^A}{K^{Amax}}\right)^{\gamma_2},$$

where $0 < \gamma_2 < 1$ is a parameter that indicates the extent of diminishing returns to protection. The higher $\gamma_2$ the less diminishing returns are, such that the limit of $\gamma_2 = 1$ implies that the marginal protection of adaptation capital is constant. $\gamma_1$represents the effectiveness of adaptation investments, if $\gamma_1$equals one and $K^A = K^{Amax}$ protection would be complete ($P = 1$).

We follow de Bruin, Dellink and Tol (2009) and De Cian *et al.* (2016) in distinguishing between gross ($GD$) and residual damages (RD).Residual damage from a given climate even in year t, $RD_t$, is equal to the product of gross damage in that year, $GD_t$ , and the level of protection $P_t$ at time $t$,

$$RD_t = (1 - P_t)GD_t.$$

An economy without adaptation capital ($P = 0$) will be affected by the full force of climate damage. A country that achieves a protection level of one would experience zero damages from flooding.

The amount of investments $K^A$ is a policy choice of the government. We can expect the government to set $K^A \leq \overline{GD}$ (the expected amount of damages in any given year). Otherwise the economy would expend more resources on adaptation investments than actual expected flooding damage. How much less than $\overline{GD}$ will depend on the opportunity costs of the money spent on the investments, the effectiveness of different levels of protection and society's tolerance for variability in the level of output.

Because there is very little data that would allow for a convincing calibration of the effectiveness of flooding adaptation in Pakistan, we follow de Bruin, Dellink, and Tol (2009) in setting the curvature parameter of the protection function, $\gamma_2$, to 0.3 (close to the inverse of their parameter of 3.6). The effectiveness parameter is set to $\gamma_1 = 1$, implying that if an amount equal to the expected value of flooding damages were invested each year in adaptation, the productive capital stock would be fully protected from flooding. For a description and robustness results for different calibrations, see examples in Burns, Jooste, and Schwerhoff (2021).

### 3.9.1 Accounting for the opportunity costs of adaptation investments

The investment into adaptation capital needs to be considered in the calculation of GDP and government expenses. On the demand side, the standard GDP and government spending identities are modified to account for spending on adaptation capital as follows:

$$Y_t^j = C_t^j + CG_t^j + I_t^j + {I_t^A}^j + II_t^j + X_t^j - M_t^j + Stat_t^j,$$

$$G_t^T = G_t^{GS} + G_t^{WN} + G_t^I + G_t^{SOC} + G_t^{DSC} + G_t^{OTH} + {I_t^A}^{CN}$$

When running simulations, the economy-wide effects of adaptation investments will depend strongly on how the government finances adaptation investments. The government can finance these investments through higher deficits, higher taxes, reduced expenditure in any of its expenditure categories, or a combination of these.

# 4. Simulation properties

PAKMod can be used in standard forecasting, policy analysis and fiscal sustainability analyses. Its additional climate features mean that in addition to the normal macroeconomic indicators that are generated (growth, inflation, current account, fiscal account, and unemployment outcomes), the model also will generate climate outcomes, including carbon emissions produced, air pollution, and associated reductions in labor productivity, health, capital destruction and agricultural production. These results are generated whether the focus of the analysis is generating a long-term baseline, analyzing a policy change that has nothing to do with climate, or analyzing the economic impacts of alternative global climate scenarios and different climate policies.

## 4.1 The emissions module

This section presents model properties in response to climate change. The following subsection discusses the baseline and presents the outputs of the model for several standard climate-change scenarios. This includes results from the imposition of a simple carbon-tax under three scenarios. In scenario 1 the government uses the additional revenues to reduce debt (i.e. as a savings device), in scenario 2 the government imposes a revenue neutral carbon policy via a reduction in income taxes and in scenario 3 the government uses the revenue from the carbon tax as a transfer to households.

### 4.1.1 The baseline

To evaluate the model's climate properties, its outputs are compared with those coming from various Integrated Assessment Models[28] (IAMs). This requires both creating a baseline or "business as usual" (BAU) scenario, which will serve as a reference for various policy scenarios. To anchor the baseline a set

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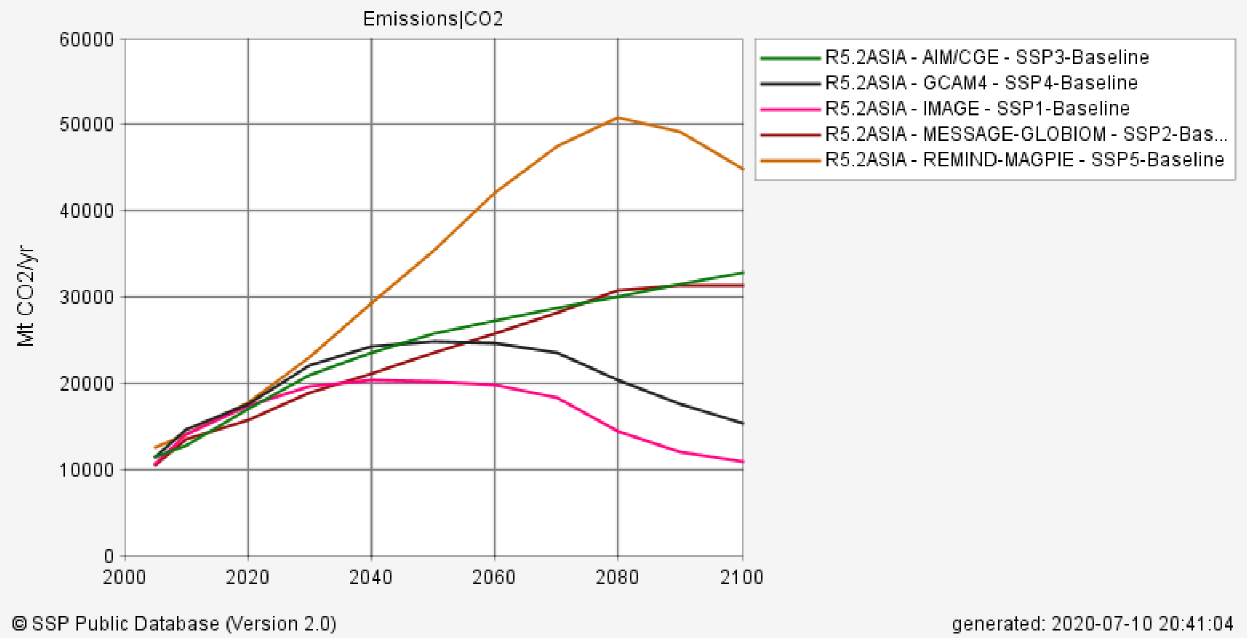
[28] Integrated Assessment Models (IAMs) are integrated climate-macro models, which are constantly developed by entire teams of researchers over long time horizons (for more see https://www.iamcdocumentation.eu/). They also form an important basis for the assessments of the Intergovernmental Panel on Climate Change (IPCC). We can thus use their baseline scenarios as a benchmark for our baseline. In this subsection we will thus discuss what the benchmark baselines look like and then how to approach the baseline.

of common assumptions about future developments in terms of demand, technology and climate change are employed.

Climate modelers have developed Representative Concentration Pathways (RCPs) for future emissions based on standardized assumptions about the level of mitigation effort at the global level, and Shared Socioeconomic Pathways that comprise a set of assumptions on socioeconomic conditions. Figure 12 shows $CO_2$ emission trajectories for RCP 8.5 (“baseline”) and the five SSP scenarios for South Asia. Unfortunately, these scenario data are only available at a regional level, not at a country level.[29]

Figure 12: $CO_2$ emission trajectories for Asia in a BAU emission scenario for different SSP scenarios



Source: Riahi *et al.* (2017)

Figure 12 shows that very different trajectories are possible, even for a given assumption on climate policy. The results, which are for South Asia not Pakistan, show emissions rising steadily until 2100 and reaching a multiple of today’s level – an outcome that if followed globally would likely have catastrophic consequences (World Bank 2012).

The emissions trajectory of PAKMod (third chart in Figure 13) is roughly consistent with the results for RCP 8.5, where emissions are projected to double by 2080 before beginning to decline.

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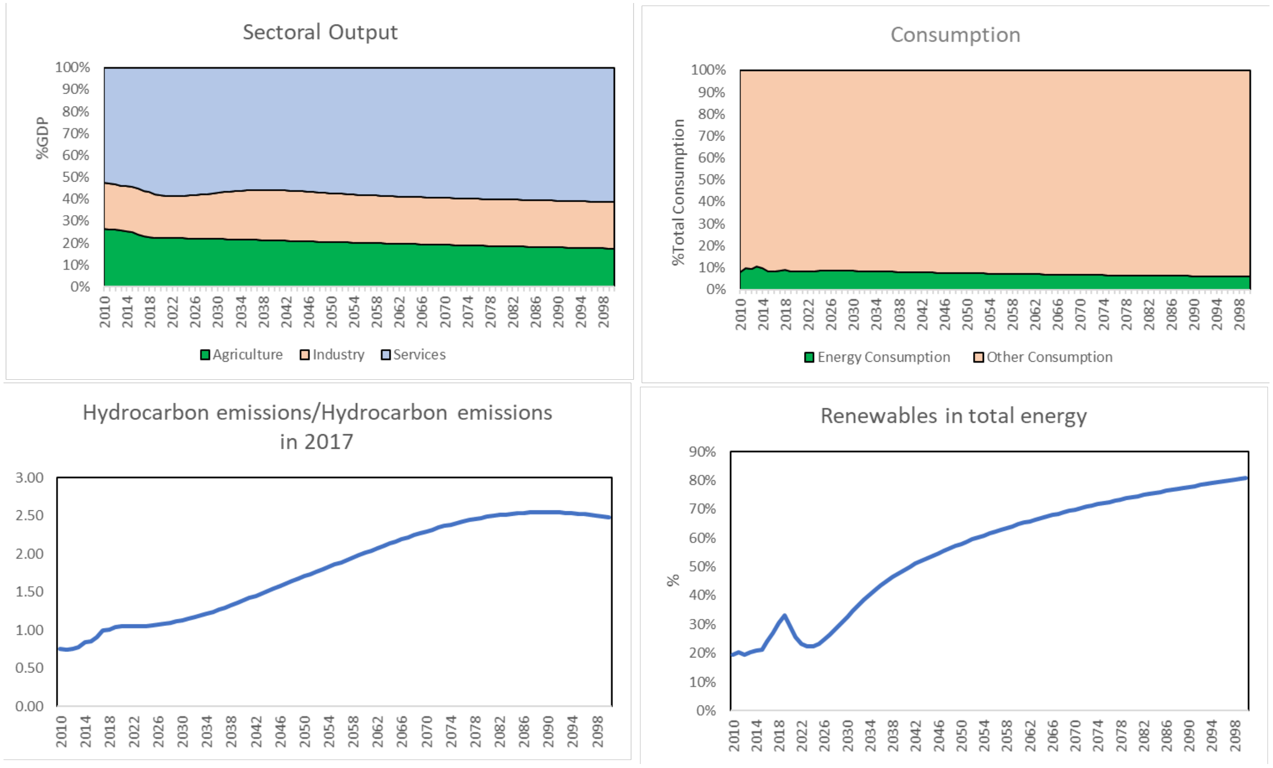
[29] The data were accessed from the SSP public database at https://tntcat.iiasa.ac.at/SspDb/. Details about the data set can be found in Riahi *et al.* (2017).

Figure 13: Sector output, energy consumption and baseline emissions



The calibration in PAKMod is done to generate consistent results. For a given level of GDP, the emission trajectory from energy depends on 1) the energy intensity of different economic activities; 2) the carbon intensity of different energy sources; and 3) the shares that each energy source has in total energy production. The declining energy intensity of the economy during the projection period is common to most countries and reflects both technological progress in the efficiency of energy use and structural change. A growing service sector, which is less energy intensive than manufacturing or agriculture will tend to lower emissions per unit of GDP.

A major determinant of the shares of each energy source in total energy are their relative prices.[30] In PAKMod the nominal price of most commodities (including fossil fuels) is projected to grow at the rate of inflation, meaning that their growth is zero in real terms. Renewable energy prices are assumed to decline by 1.5 percent per annum in real terms over the projection period in line with history (renewable prices have fallen much more quickly – about 15% per annum). Figure 14 shows the price trends for coal, oil and gas from 1960 to 2020. The prices are taken from the World Bank Commodities Price Data (The Pink Sheet) and are deflated with the US Consumer Price Index (CPI) of the Federal Reserve Bank. Prices are normalized to January 1970. The data shows that fossil fuel prices are roughly constant in the long term. This is in line with the literature on long-run resource prices (Krautkraemer 1998).

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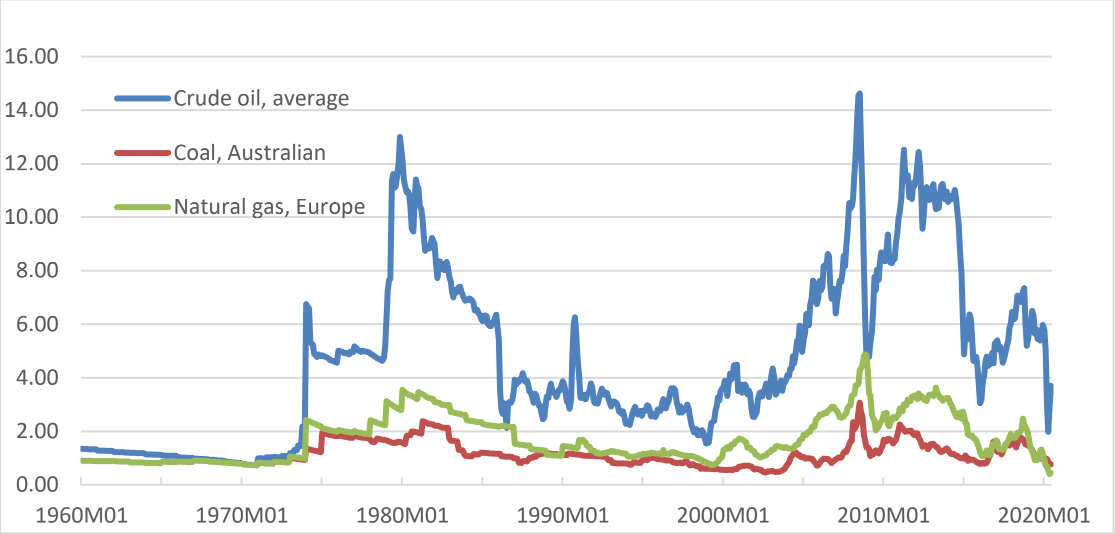
[30] See eia.gov.outlooks/aeo/section_issue_renewables.php for a comparable projection of renewable prices through 2050.

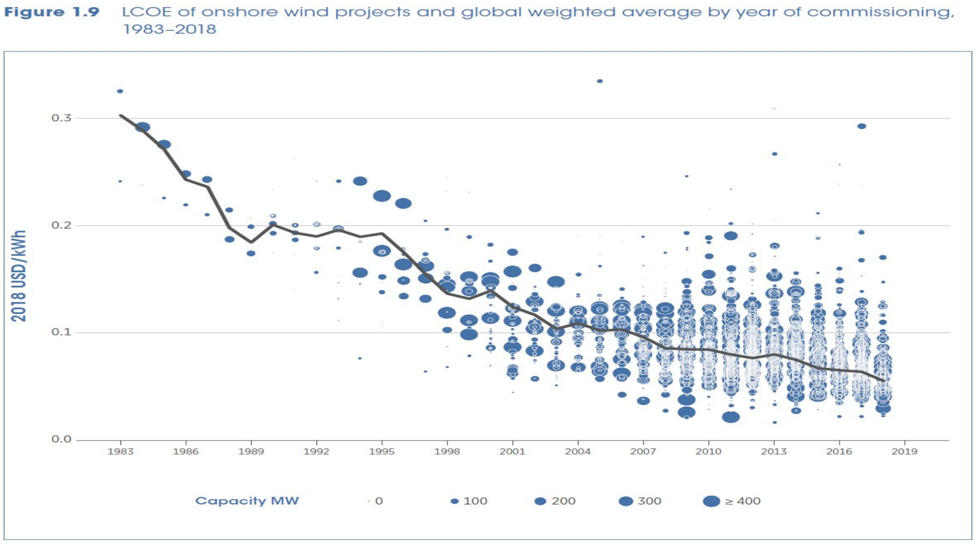
Figure 14: Real prices of various fossil fuels (1970=1)



Source: World Bank Commodities Price Data (PINK SHEETS)

In contrast the real price of renewable energy has been falling since the 1980s (Figure 15 and Figure 16). The real levelized cost of electricity (LCOE) expressed in 2018 dollars for onshore wind has gone from a weighted average of 0.303 USD/kWh in 1983 to 0.055 USD/kWh in 2018 (IRENA 2019). This is an average decline of -4.8% per year. The total installed costs for solar photovoltaics was 4621 USD/kW (in 2018 USD) in 2010 and 1210 USD/kW in 2018. This corresponds to an average growth of -15.4% per year.

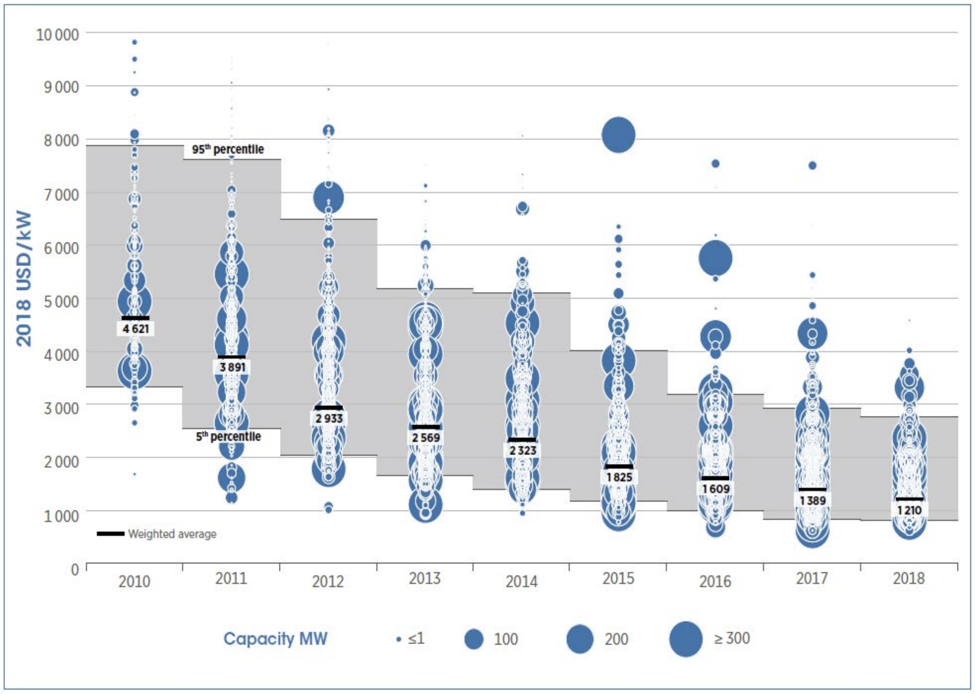
Figure 15: Price trend for onshore wind



Source: IRENA (2019)

Figure 16: Cost for solar PV

**Figure 2.2** Total installed cost for utility-scale solar PV projects and the global weighted average, 2010–2018



Source: IRENA (2019)

The relative price of renewables falls throughout the baseline forecast. This contributes to a steady substitution away non-renewable fuels to renewables, which serves to reduce the carbon intensity of the economy overtime. While economic growth causes emission to rise over time, by the end of the projection period the renewable energy price effect and the structural change in the economy dominates and the actual level of emissions begins to fall. It is, however, hard to pin down the price trajectories of commodities and renewables. The historical changes in prices are used in the baseline case. We repeat several of the simulations using an alternative baseline. This alternative baseline keeps the relative price of renewable to hydrocarbons constant throughout the projection period. The substitution effects disappear without climate policy and consequently emissions rise throughout the projection period (see Appendix 4A for more details).

The substitution toward renewables is only partial and follows Carrara and Marangoni (2017). We assume that the production of energy follows a nested constant elasticity of Transformation (CET) structure similar to that of the model WITCH, with a high long-run substitutability between fossil fuels and renewable energy of 5 in the production of electricity, and a low elasticity of substitution between electricity and other energy of 0.5.

Based on these assumptions, and the historical expansion of productivity in the Pakistani economy, PAKMod baseline emissions increase by close to a factor of two by 2100, which is broadly in line with other model projections as in Figure 12.[31] The model's dynamics are based on the estimated elasticities, rigidities (prices and wages) and speed of adjustment to equilibrium. The CES structure for energy demand differentiates between short and long-run elasticities. This is in line with the discussion earlier where the existence of sunk costs in energy plants means that the economy will not react immediately to the imposition of a carbon tax. Older plants may continue to run as long as their marginal costs (net of sunk construction costs) lie below the net of tax market price of energy. Full adjustment will occur only gradually as these plants age and are eventually scrapped because renovation costs would be too high. Fossil fuel fired plants may be abandoned immediately when the operating costs of existing plants exceed the electricity price. This might apply to plants near the end of their life cycle. An agreement between Pakistan and the Russian Federation (Pakistan Stream Gas Pipeline) is a multibillion-dollar project that aims to connect LNG terminal between the south of Karachi and Lahore in the north-east.[32] While gas emits considerably carbon dioxide, the sunk capital into this project will inevitably slow down the no-carbon energy transmission in the short-term.

### 4.1.2 Mitigation scenarios

The model changes described above allow us to examine the economic impact of different policies to reduce carbon emissions. In what follows a carbon price of 2,500 Pakistani rupees (PKR) per ton of $CO_2$ (roughly \$20) is introduced, under three alternative assumptions about the uses made of the revenues collected. In the first, additional revenues are recycled by expanding the social security system, effectively transferring the collected revenues to households to spend on their own priorities. In the second the revenues are used to reduce debt. In the third, the additional revenue is used to reduce other taxes, notably the direct tax rate (the revenue neutral tax reform scenario).

The carbon tax is applied in real terms, thus the nominal amount rises in line with inflation over time. While the amount of the carbon tax is somewhat arbitrary, it is roughly in line with the price in the European Union Emissions Trading System (EU ETS), which has varied between 20 and 30 USD between September 2018 and July 2020. Imposing a \$20 carbon tax in the context of Pakistan implies a much larger than \$20 per ton price increase because currently, hydrocarbon fuels are subsidized. These subsidies mean that the implicit price of carbon has been negative (and applied at different rates for different products). For example, a \$20 carbon tax would imply an increase in the carbon tax on natural gas of more than \$60 (currently the carbon content of natural gas is subsidized at just a bit more than \$40 per ton).

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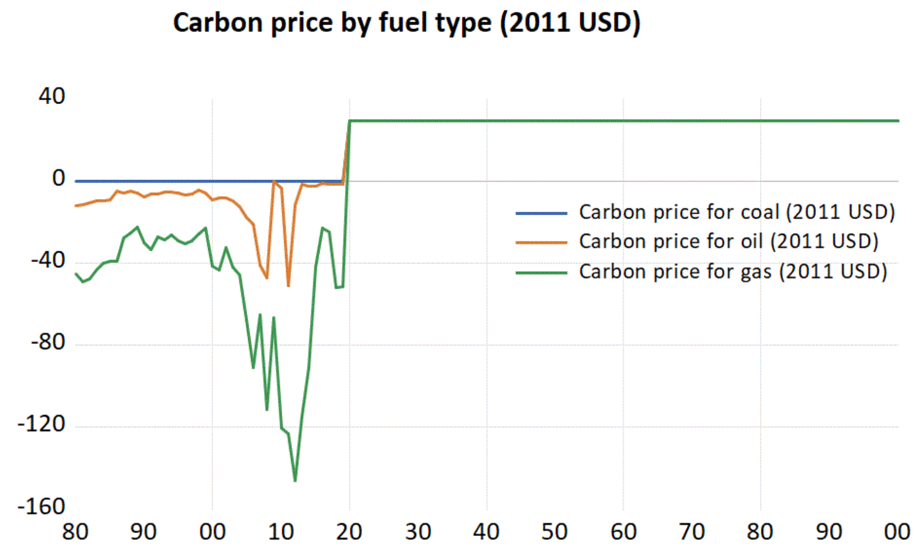
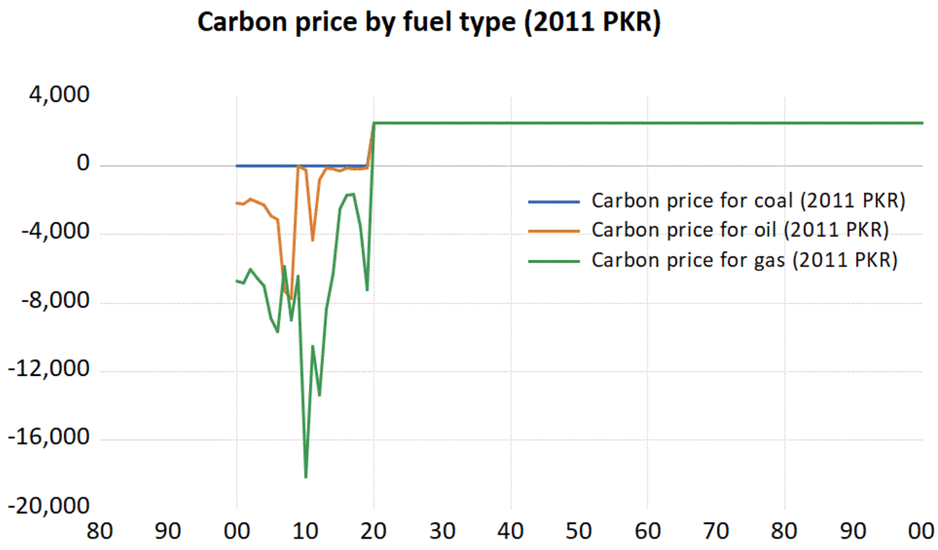
[31] It is worth noting, however, that these outcomes are significantly lower than the projections produced by the Government of Pakistan in the context of the 2015 Paris Agreement. Pakistan's "Intended nationally determined contributions" (INDC) (Government of Pakistan 2016) submission implied a near tripling of $CO_2$ emissions, the bulk of which was expected to come from the energy sector. Indeed, data submitted by the authorities implied that the rate of growth of emissions from the energy sector would triple an average annual growth rate of 4.7 percent between 1994 and 2015 to one of 11 percent for the period 2015 to 2030, an acceleration that the authorities attribute to an "accelerated growth scenario of the energy sector" (Government of Pakistan 2016).

[32] https://www.bloomberg.com/news/articles/2020-12-16/pakistan-to-start-building-lng-pipeline-with-russia-in-july

Figure 17: The carbon prices in Pakistan



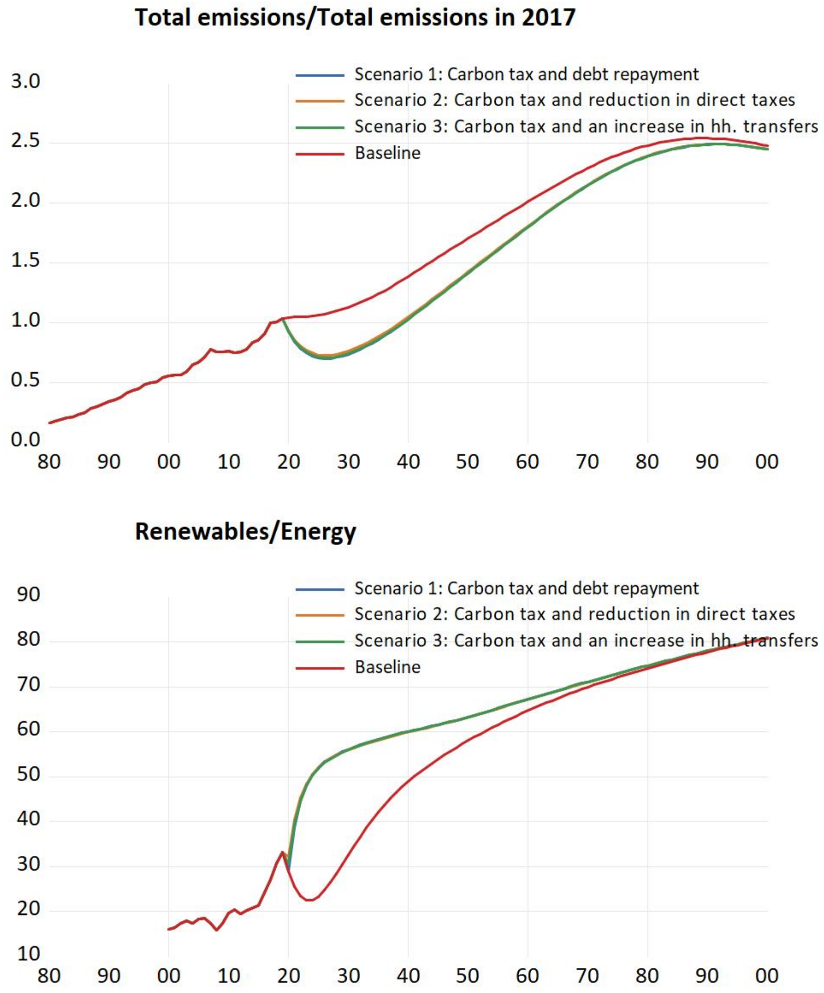


Historically, the carbon price equivalent of fuel subsidies has been highest for gas and oil, so implementation of a uniform carbon tax raises their carbon prices most. The negative carbon prices prior to 2017 reflect subsidies that reduce the market price of various fuels in Pakistan. Despite the historically large negative carbon price for coal, the total carbon tax rate is much less negative because until recently Pakistan has not used much coal to generate energy. The historic movements in the implicit subsidy are mainly driven by price fluctuations in the market price of oil and gas in the face of a constant regulated price, as well as a reduction in carbon subsidies in the last few years before 2017. In the absence of more recent data, it is assumed that the real carbon price in 2018 and 2019 is unchanged from 2017.

*Economic impacts*

Figure 18 reports the simulated impact on emissions from energy of imposing a $20 real carbon tax in 2020. In the top panel, the 2017 value of energy-related emissions is set equal to one, so that the vertical axis can be read as multiples of the 2017 emissions. The growth in emissions reflects the growth of the Pakistani economy, partially offset by falls in quantity of energy required per unit of GDP. While the carbon price has a visible effect on emissions, it does not halt the growth in emissions immediately, which is dominated by economic activity. After 2080 emissions decline even in the baseline because of an assumed shift in relative energy prices in favor of renewable energy as the prices of the former declines by 1.5 percent annually. The increase in the share of renewable energy in the bottom panel is at the high end in the literature, but comparable for example to the trajectory shown in Figure 9 of Sadiqa, Gulagi, and Breyer (2018).

Figure 18: Emission trajectory in Pakistan under different scenarios



**Total emissions/Total emissions in 2017**

**Renewables/Energy**

Notes: Emissions refer to hydrocarbon emissions primarily, and not those associated with agriculture, cement, and other industrial and chemical processes.

Figure 19 reports the simulated impact of the imposition of the carbon price on the macroeconomy, under each of the three revenue disposal scenarios. In scenario 1, Higher prices and inflation cause GDP and consumption to fall initially compared with the baseline. Energy prices increase, so that production becomes more expensive, although the impacts are modest -- less than 1% loss in GDP and less than 2% in consumption. Subsequently, the economy catches up with the baseline for GDP, as the economy adjusts to the new price levels and because the revenue from the carbon tax allows the debt to be paid down. This in turn lowers debt service charges and frees up economy-wide savings for private sector investment. Lower debt levels and reduced demand for savings, reduces the sovereign risk premium and the cost of investment and encourages more private investment, and results in a higher capital stock and eventually higher levels of potential GDP.

In scenario 2, carbon tax revenues are used to reduce taxes on capital and labor in the formal sector. The reduction in these taxes alleviates the initial income losses due to higher energy costs. As a result, the initial GDP and consumption impact is positive. Note that the initial response in consumption reacts to an increase in disposable income immediately. Liquidity constrained households spend the higher incomes immediately which causes the initial growth in this scenario to exceed the baseline. While the level effect is larger than the baseline in subsequent periods, the growth in consumption is more moderate in those periods. The new relatively broad carbon tax causes fewer economic distortions than the direct taxes that it replaced. In particular, the decrease in the labor tax (which falls only on formal employment) increases formal employment where productivity is higher and as a result overall output is boosted. Lower direct taxes also reduce the cost of investment, which contributes to an uptick in the capital stock and potential GDP.

In scenario 3, carbon tax revenues are recycled back into the economy as a transfer to households. As a result, despite higher consumer prices, increases in household income translate into an initial boost in GDP and consumption that is only gradually eroded by inflation. In the long run the income effect is eroded by higher prices and so GDP gains are minimal. Higher prices generate a small reduction in debt to GDP, but this is mainly due to the inflationary response.

In all three scenarios increased hydrocarbon prices reduce imports (lower right panel of Figure 19), which as an initial effect, reduces the current account deficit and the domestic demand for foreign saving, contributing to a reduction in domestic interest rates and capital accumulation.

Figure 19: Macroeconomic responses to carbon taxes

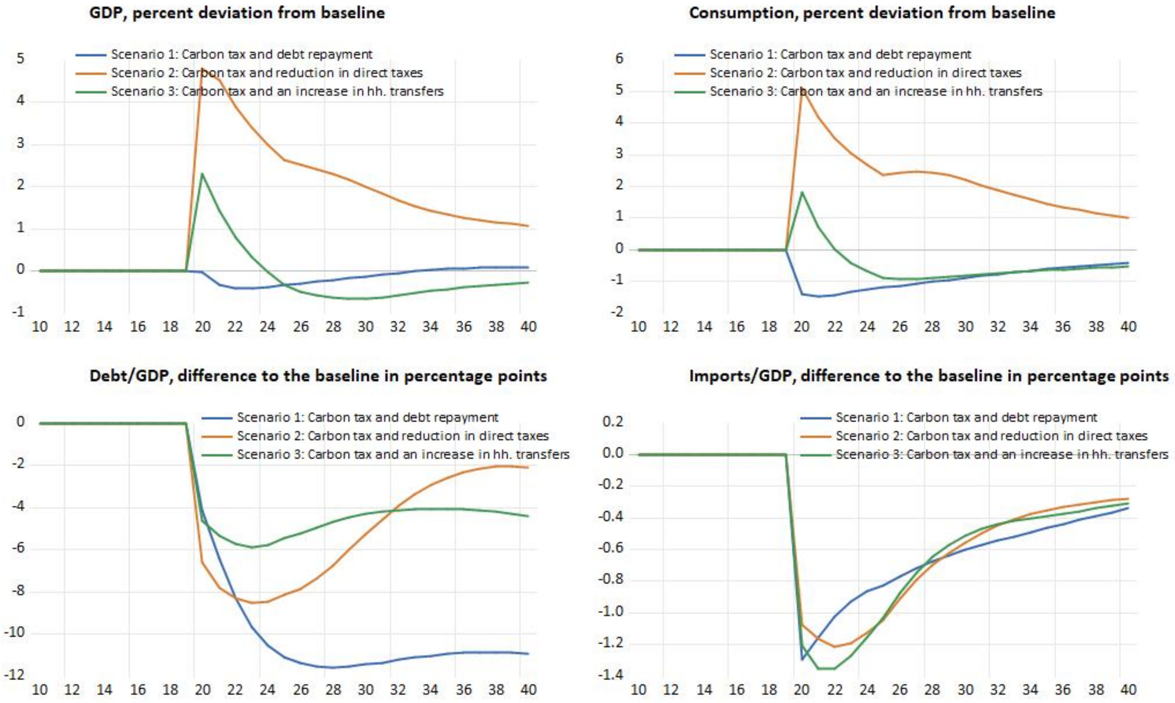
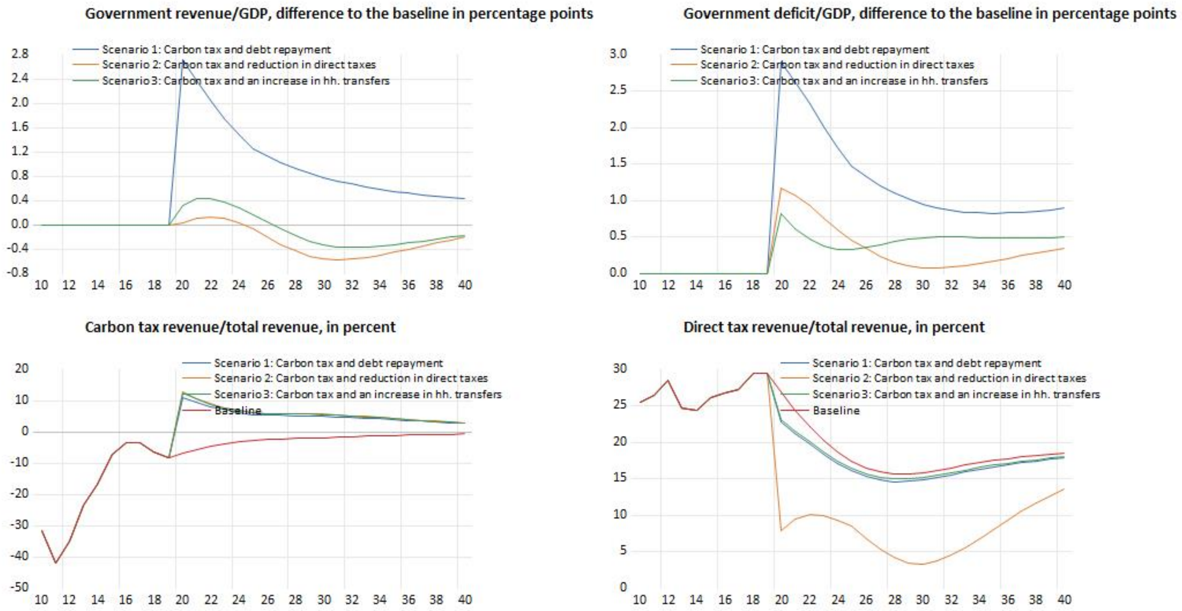


Figure 20 explores the impacts of the three scenarios on the government's finances. The two top panels again illustrate that scenario 1 raises additional revenue while scenarios 2 and 3 recycle the revenue. The bottom left panel shows that fossil fuels, which have been a significant government expense (in the form of energy subsidies) become a source of revenue (in the form of a carbon tax). The bottom right figure shows that the share of direct tax in total revenue falls through the tax reform. Furthermore, note that as carbon emissions decline over the forecast horizon, carbon tax revenue collections decline. As a share of GDP, they decline even more markedly as not only are emissions and therefore revenues falling, the denominator is also growing. The revenue-neutral policy is thus only temporary. This is offset to some extent with a larger general tax base as GDP improves.

Figure 20: Government finances in the three scenarios


Government revenue/GDP, difference to the baseline in percentage points

Government deficit/GDP, difference to the baseline in percentage points

Carbon tax revenue/total revenue, in percent

Direct tax revenue/total revenue, in percent

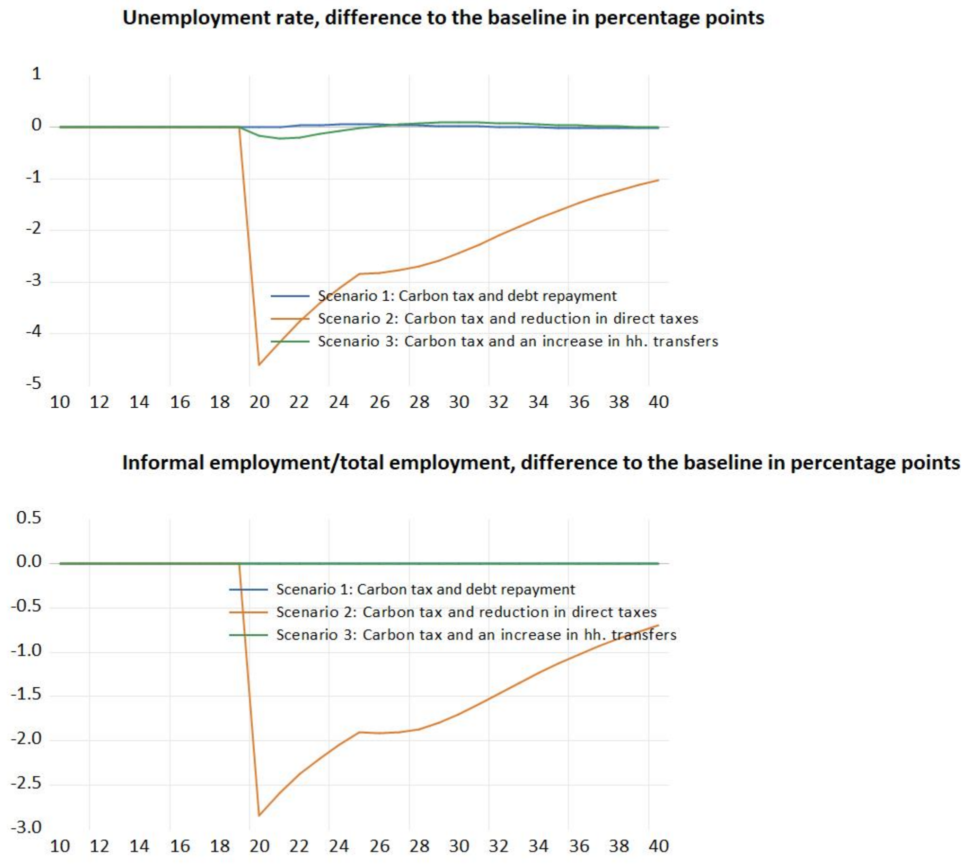
### 4.1.3 Labor market effects

In the second simulation, when revenues from the carbon tax are used to reduce taxes in the formal sector, there is a net increase in economic efficiency as the incentives to remain in the informal sector decline and more firms move into the formal and benefit from network externalities.

In the saving scenario, where carbon tax revenues are used to pay down the debt, the initial slowdown in the economy leads to a slight increase in unemployment, which follows the reduction in production due to higher energy prices. The unemployment effect is temporary – initially responding to a fall in aggregate demand but then decreasing as demand recovers and potential output responds to the lower interest rates and higher investment rates. By contrast in the tax switching scenario 2, unemployment initially falls by 4.7% as firms react to the reduction in interest rates and higher demand due to a reduction in income taxes. As the economy equilibrates and as the economy transitions away from fossil fuels (and hence a lower carbon tax burden), unemployment returns to its baseline level. In scenario 3 the government transfer to households generate a temporary reduction in unemployment before returning to baseline.

Changes in formal and informal employment are central to the relatively large gains in the tax switching scenario. The share of informal labor in total employment is unchanged in scenarios 1 and 3 because the relative price of formal and informal labor is untouched by the carbon price in these scenarios. In the tax switching scenario, however informal employment declines relatively sharply because the carbon tax revenues allow the government to lower labor taxes in the formal sector. As a result, formal labor gets cheaper and firms bring more workers into the higher productivity formal sector.

Figure 21: The effect of carbon tax reform on the labor market

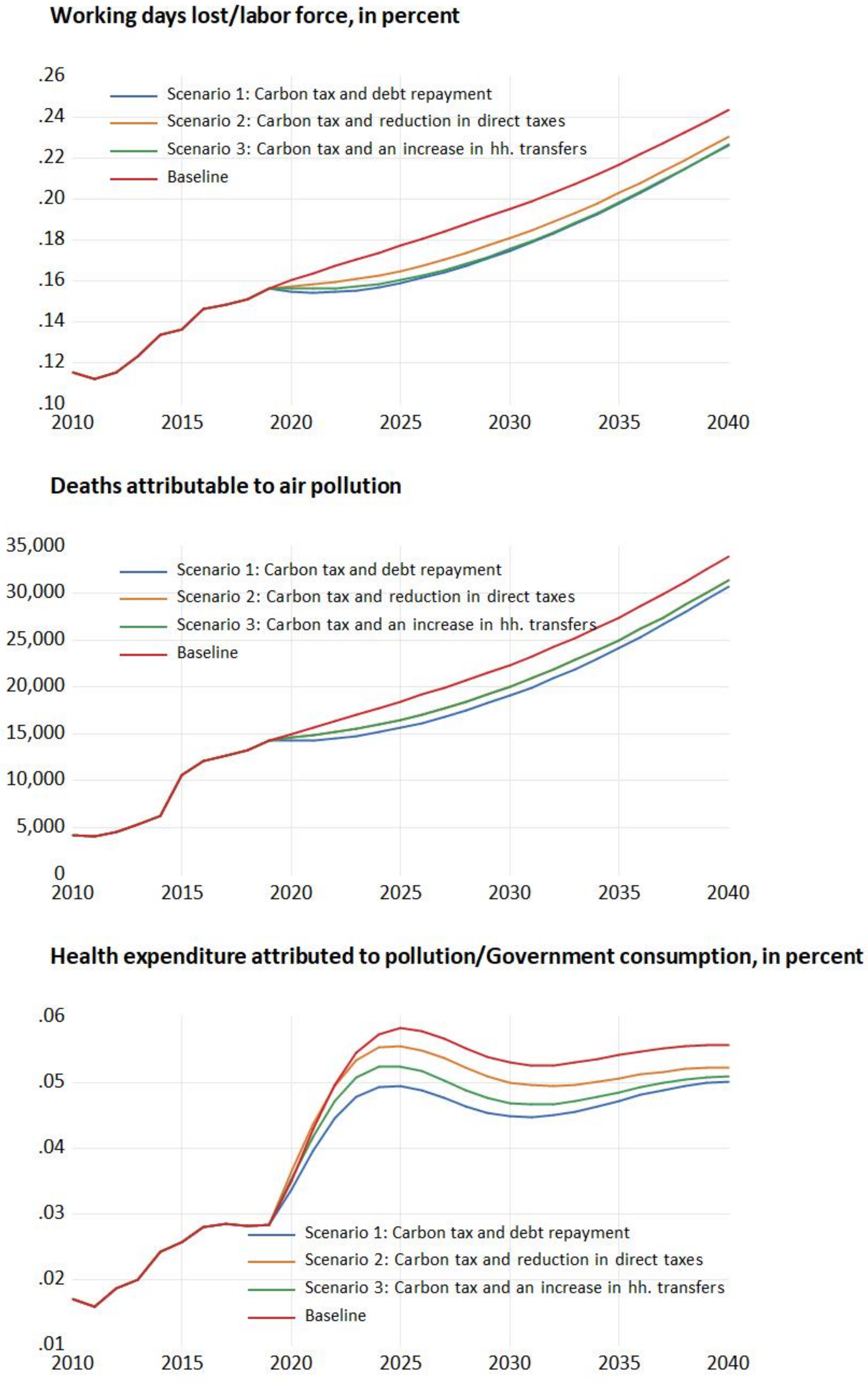


### 4.1.4 Co-benefits: Pollution emissions and health impacts

Figure 22 shows the effect of the carbon price on air pollution. In 2017, estimates from the CPAT model suggest that 0.145% of all potential working days were lost due to air pollution and an estimated 12,649 Pakistani citizens died because of air pollution. In the baseline, fossil fuel consumption is projected to grow and, with it, local air pollution. This results in an increasing trend in working days lost due to air pollution (see the top panel).

As the carbon price makes fuel consumption more expensive, local air pollution falls relative to the baseline and the number of pollution related deaths and working days lost declines.

Figure 22: The effect of carbon taxation on air pollution

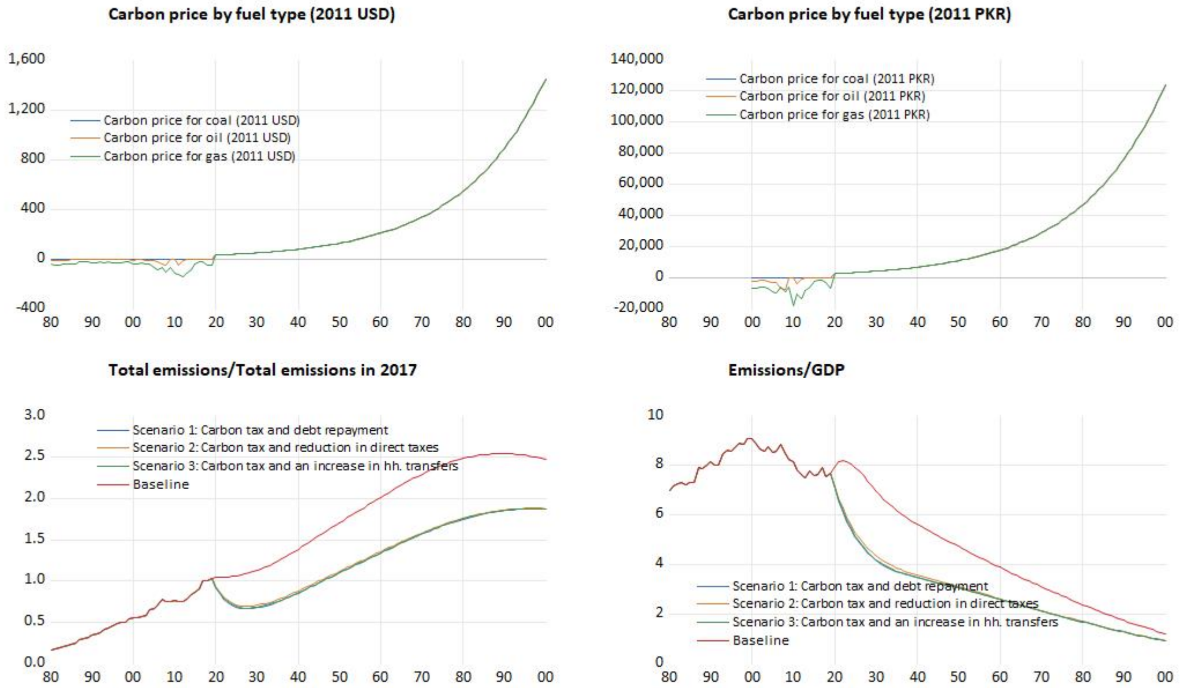


### *More ambitious climate policy*

In the next set of simulations, the implemented carbon price is increased to incite an even larger decarbonization of the economy. Initially the carbon price is the same as in the previous simulations but starting in 2021 the carbon price is increased a further 5% per year in real terms. This results in real carbon prices of 30 USD (27 EUR) and 60 USD (54 EUR) in 2027 and 2041, values at the low-end and midpoint the OECD (2018) estimates of the carbon prices among OECD member countries in 2020. Sweden has a carbon tax of 119 USD already (World Bank 2020a), a level not reached in this scenario until 2057. Because of compounding the carbon price in the end period reaches a very high of about 1400 (2011 USD) in 2100. As Figure 23 shows, this level of climate policy slows the rise in energy-related emissions, but they nevertheless almost double from 2017 levels.

In the steady state, after full adjustment to the very high carbon prices at the end period, carbon levels are about 70 percent higher than the 2017 level, whereas it would have been roughly 150 percent higher with no carbon price. In all three revenue-use variants carbon emissions from energy per unit of GDP decline to close to zero (Figure 23).

Figure 23: Prices and emissions in the case of moderately ambitious climate police



Notes: Emissions refer to hydrocarbon emissions primarily, and not those associated with agriculture, cement, and other industrial and chemical processes.

### *Highly ambitious climate policy*

The final set of simulations represents a high-ambition scenario, in which carbon prices grow at 8% per year in real terms. The level of 30, 60 and 119 USD levels are attained in the years 2024, 2033 and 2044, respectively. In these scenarios, emissions initially fall to as much as 65% of their 2017 levels before gradually rising to just above that level as the economy grows. Endpoint carbon prices in this scenario are extremely high, more than $12,000 per ton by 2100.

The remaining carbon output even at unrealistically high prices reflects the modeling of different energy sources as complements. This modeling choice generates reasonable substitution behaviors given current technologies and energy sourcing. However, it excludes the possibility of eliminating carbon-sourced energy at any price. The modeling choice is realistic in the short term, especially given the absence of a green energy alternative for uses such as aviation that rely on the high energy/weight ratios of hydrocarbons. However, it excludes the possibility that very high carbon prices generate an endogenous technological change such as the commercialization of green hydrogen technologies generated from renewable fueled electrolysis, that could permit even greater decarbonization in the long run.[33]

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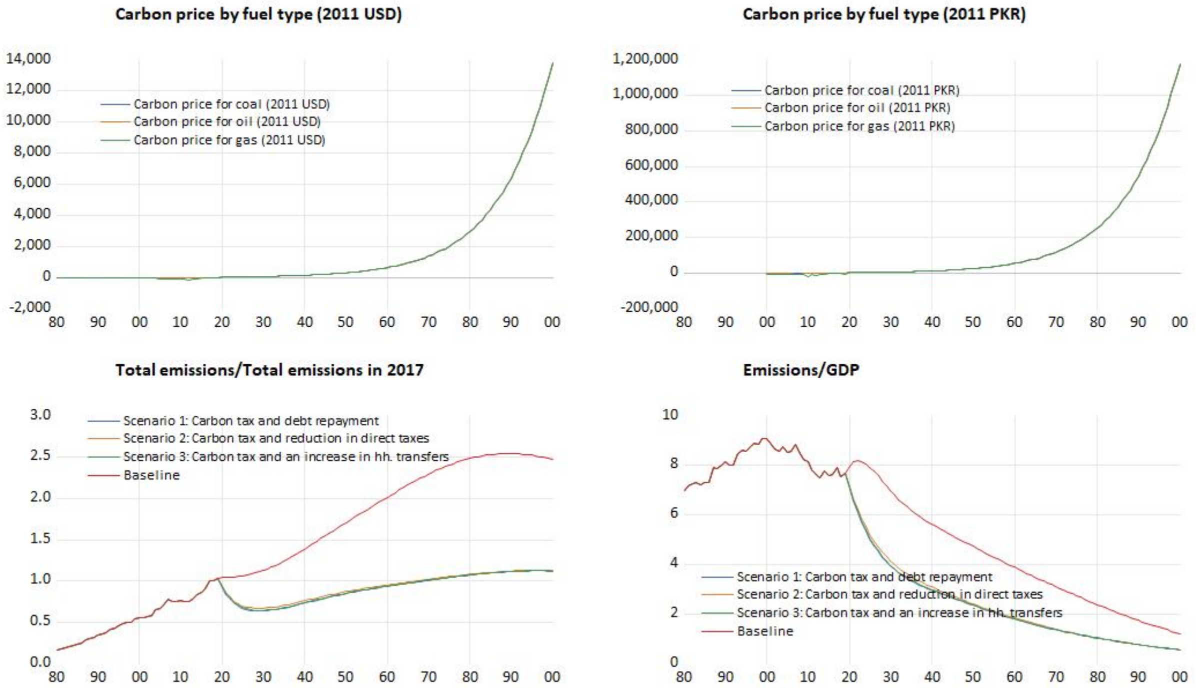
[33] The World Bank has released a report on "The Potential of Zero-Carbon Bunker Fuels in Developing Countries" recently: https://openknowledge.worldbank.org/handle/10986/35435. It shows that zero-carbon fuels for aviation and shipping are not so unrealistic anymore.

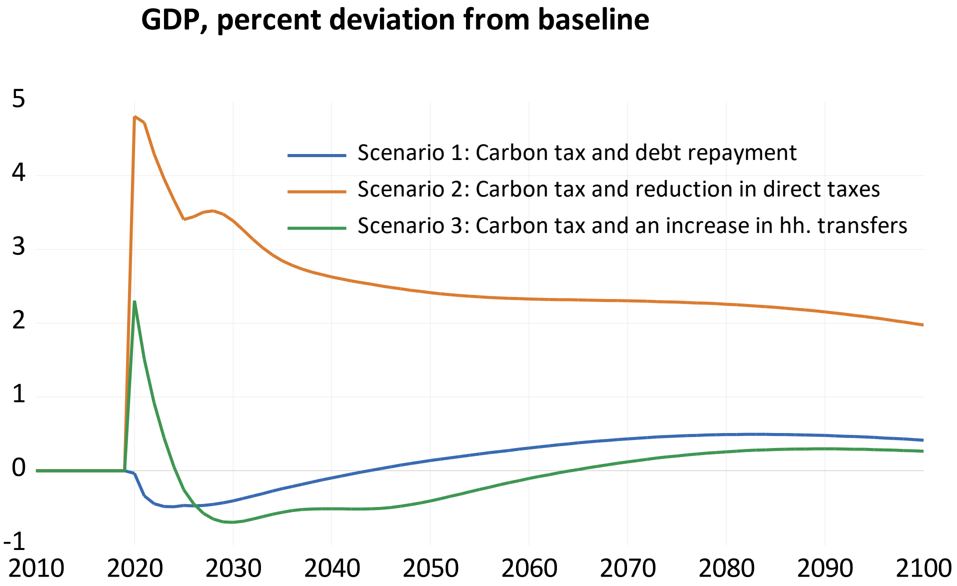
Figure 24: Prices and emissions in the case of highly ambitious climate police



Notes: Emissions refer to hydrocarbon emissions primarily, and not those associated with agriculture, cement, and other industrial and chemical processes.

Consistent with the $20 carbon price scenario, modest positive effects for GDP are generated even in the extreme effect due to reduction in overall debt that increase available savings for investment, lower interest rates and ultimately increase potential output. This effect is amplified in the tax switching scenario as lower direct taxes incite workers to move from the informal to the formal sector where productivity levels are higher.

Figure 25: GDP in the case of highly ambitious climate policy 8% per year



## 4.2 Climate change and economic performance

As discussed above, climate change will have deleterious effects on the economy. This section quantifies the impacts on labor productivity, agricultural output from higher temperatures and increased rainfall variability, including the damage caused by flooding.

Three simulations are presented. The first is a counterfactual baseline scenario where it is assumed that there will be no further climate change. This hypothetical baseline case is only presented to help quantify the economic consequences of the climate change that Pakistan is likely to undergo over the coming decades. Two additional simulations are based on two climate scenarios developed by climate scientists, see Table 7. These damage scenarios are based on the representative concentration pathways RCP 2.6 and RCP 8.5. RCP 2.6 is used to reflect an attainable mitigation scenario, being the pathway closest in line with the targets of the Paris Agreement. RCP 8.5 is used as a “Business as Usual” (BAU) scenario. While we recognize that there is an emerging consensus that without climate policy, emissions will not be as high as assumed in the RCP 8.5 scenario (Hausfather and Peters 2020), we nevertheless use RCP 8.5 because of the abundance of data and analysis that exists for this scenario, which should facilitate evaluation of PAKMod results.

PAKMod includes five kinds of climate damages, two damages associated with changed productivity due to climate change (declines in labor productivity due to higher temperatures; and declines in agricultural productivity due to higher temperatures and changes in rainfall patterns); two damages associated with reduced labor supply (days lost and lives lost due to pollution); and one associated with the increased incidence of extreme weather events (increased incidence of flooding).

In order to link the RCP scenarios to temperature changes, we use the temperature estimates for the RCPs provided in IPCC (2014b), see Table 7. The year 2020 is the first year of the forecast period. The data for 2050 and 2100 are taken directly from Table SPM.2 in IPCC (2014b). The value of 0.5 for the year 2020 is based on a simple linear interpolation of the IPCC (2014b) forecast that ”the global mean surface temperature change for the period 2016–2035 relative to 1986–2005 will likely be in the range of 0.3°C to 0.7°.

Table 7: Projected change in global mean surface air temperature (mean estimate) for the mid- and late 21st century relative to the reference period of 1986–2005

| | 2020 | 2050 | 2100 |
|---|---|---|---|
| **Baseline** | 0.5 | 0.5 | 0.5 |
| **RCP 2.6** | 0.5 | 1.0 | 1.0 |
| **RCP 8.5** | 0.5 | 2.0 | 3.7 |

Source: IPCC (2014b)

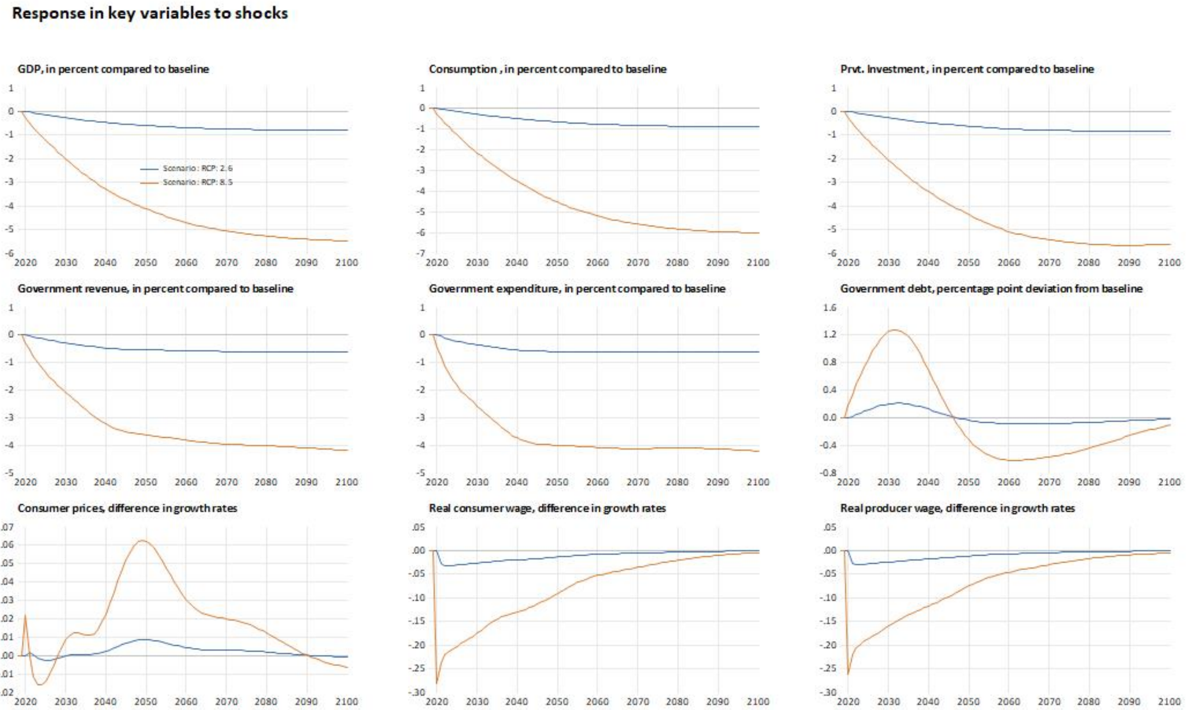
### 4.2.1 The impact of heat on labor productivity

The effects for the two RCP scenarios are shown in Figure 26. RCP 2.6 is shown in blue and RCP 8.5 in orange. Each are expressed as a percent deviation from the counterfactual baseline where there is no climate change. In each scenario, higher temperatures reduce labor productivity and therefore potential output and production. This has direct impacts on GDP, consumption and private investment in the top panels. Overall, in the RCP 8.5 scenario, PAKMOD suggests that lower labor productivity will shave about 6 percent from GDP and consumption.

In line with decreasing economic activity government revenue decreases. Government expenditure follows government revenue closely as in these long-term simulations the fiscal rule is designed to ensure fiscal sustainability. Government debt increases slightly (and later decreases) because government expenditure follows the changes in revenue with a lag.

In the model, reductions in labor productivity result in a decline in potential GDP relative to market price GDP in the immediate short run. This results in moderate (but negligible) inflation. The rise in prices and the reduction in labor productivity decreases both the consumer and producer real wage through the marginal productivity of labor channel.

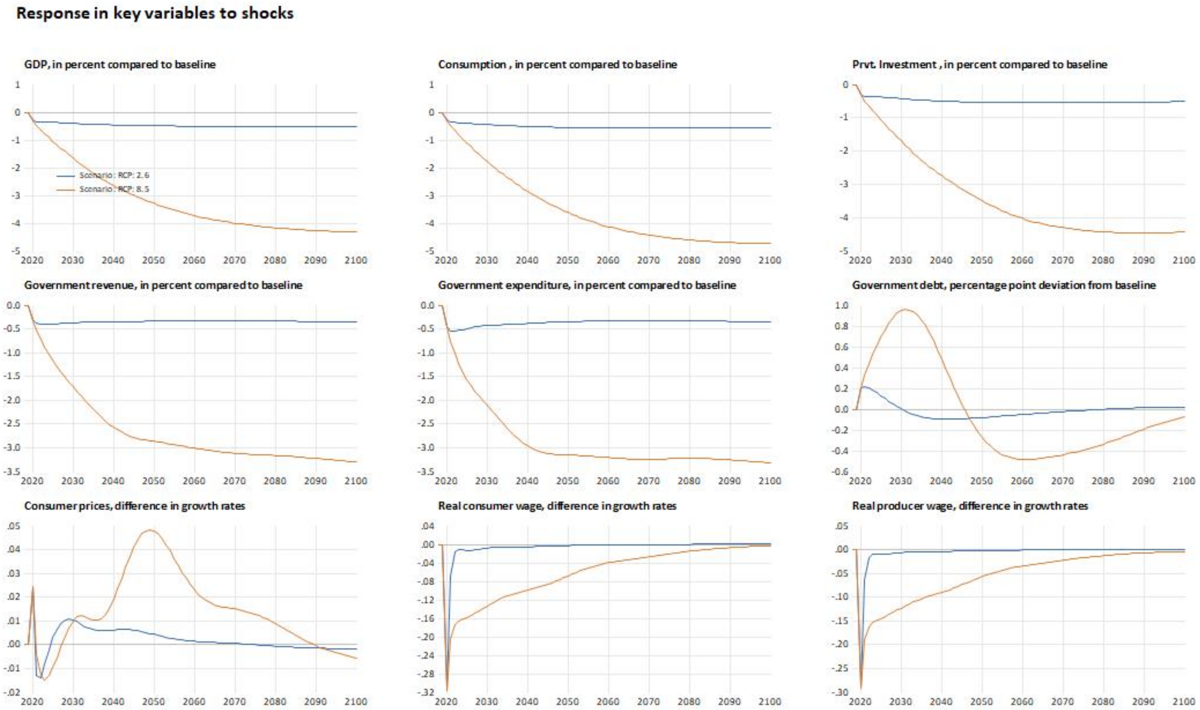
Figure 26: Effect of heat on macroeconomic variables through loss of labor productivity



### 4.2.2 The impact of climate change on agricultural productivity

Agricultural impacts from rising climate change are reported in Figure 27. As before, RCP 2.6 is shown in blue and RCP 8.5 in orange and each is compared with a counterfactual baseline where there is no climate change. The impact of climate change on the agricultural sector (top left panel) follows closely the data in Table 7, for which we have data. GDP (top left) follows the damage to the agricultural sector closely and GDP losses are projected to exceed 4% by the end of the century. Consumption (top center) and investment (top right) show a similar pattern.

Figure 27: The effect of climate change on the economy through agricultural production losses



Government revenue (center, left) follows the decrease in production. Expenditure (center) decreases following the decrease in revenue, because of the fiscal rule. Debt (center right) increases slightly because the decrease in expenditure lags the decrease in revenue. The output loss has the effect of increasing inflation (bottom left) by a small amount. Real wages are lower than in the baseline, because of lower output levels.

### 4.2.3 The economic impact of increased incidence of extreme events

As temperatures rise the frequency of extreme weather events rises (the frequency of flooding events is assumed to double for each 1 degree increase in global temperatures (see Section 3.7.6)). The distribution of economic impacts from changes in the probability of flooding damages is illustrated in Figure 28 for RCP 2.6 and Figure 29 for RCP 8.5. Each panel is showing the results of a probabilistic analysis based on 999 scenario runs with random draws of flooding damage. The dark blue line is the median scenario, the dark blue area covers the scenarios between the 25th and 75th percentile, while the light blue area covers the 10th to 90th percentile (see Table 6). As before, the baseline is a counter-factual scenario without flooding damage.

Regular flooding destroys some of the productive capital stock, and results in a lower aggregate capital stock in the scenario than in the no flooding counterfactual and results in lower levels of GDP and consumption. The debt-to-GDP ratio increases slightly as GDP falls. In the RCP 2.6 scenario the amount of damage remains unchanged relative to GDP after 2050. This allows the economy to stop deteriorating further compared to the baseline. In the RCP 8.5 scenario, however, severe flooding events become more frequent over the entire period, so that the economy moves further and further away from the baseline.

The absolute amount of economic damage, however, is quite small. By the year 2100, the median loss in GDP reaches 0.003% in the RCP 2.6 scenario and around 0.016% in the RCP 8.5 scenario. The reason for this is that, although flooding events are common, they tend to be localized and have limited impacts on aggregate GDP. Damages of more than 1% of GDP occur in less than 10% of all years and damages of over 2% of GDP occur in less than 2% of all years. Damages in the RCP 8.5 scenario are almost five times higher than in the RCP 2.6 scenario, reflecting the increased frequency of damaging storms in this scenario.

Figure 28: Impact of flooding damage on economic variables in the RCP 2.6 scenario

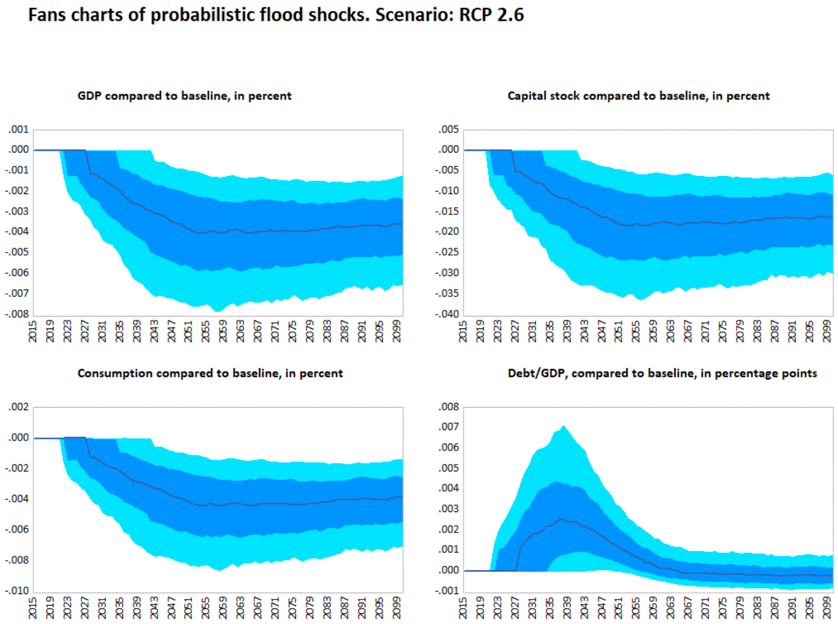
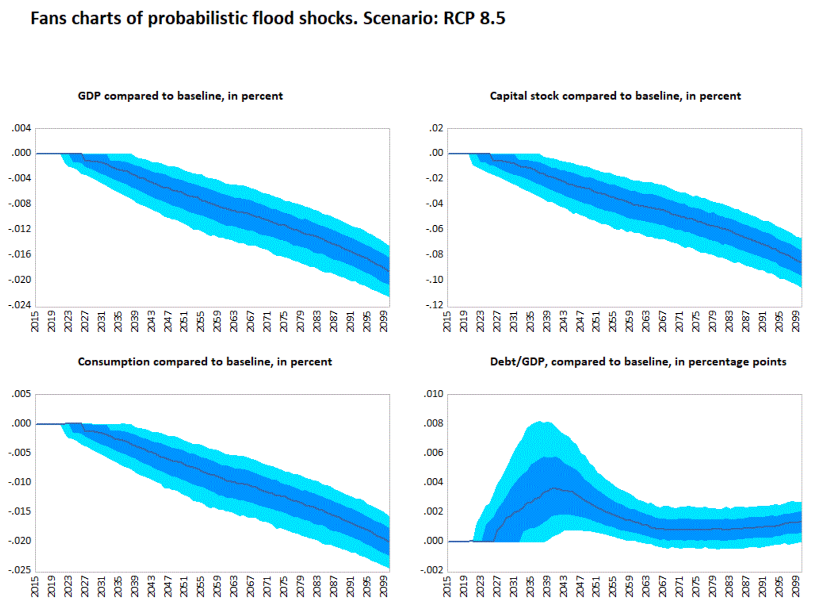
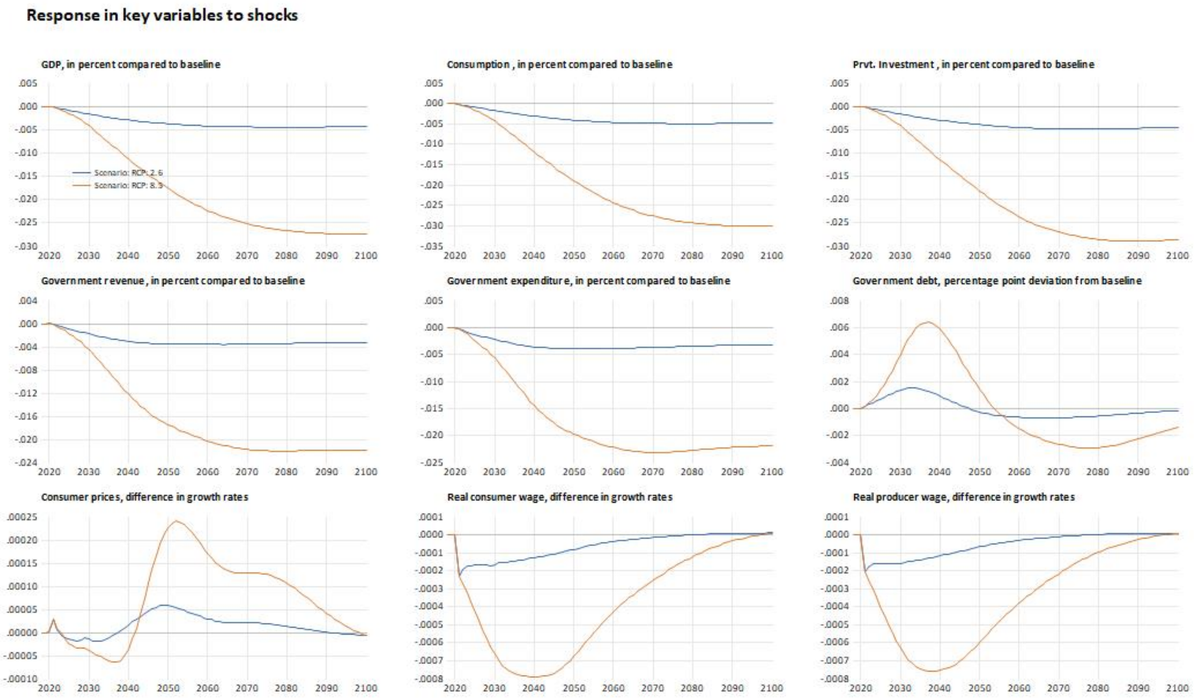


Figure 29: Impact of flooding damage on economic variables in the RCP 8.5 scenario



For comparison with the other two shocks, we also provide a graph on the economic effects that would result if flood damage would take on its expected value every year, see Figure 30. The impact on the economy is similar to the effects shown in Figure 26 and Figure 27.

Figure 30: The effect of climate change on the economy through flooding



### 4.2.4 Combined effects

While it is useful to study the impacts of climate change individually to understand the mechanisms at play, we need to consider them jointly in order to determine the magnitude of overall impacts. Figure 31 shows the combined effects of agricultural damages, the effect of heat on productivity and expected flooding damages.

According to Figure 31 total GDP losses for Pakistan from the modeled channels reach almost 10 percent of GDP towards the end of the century in RCP 8.5, but are less than 2 percent of GDP RCP 2.6. These impacts exclude unmodeled effects that might include impacts on human capital and other channels that would reduce TFP. Additional work will be needed to gather data for these additional impacts to quantify the model. Moreover, the modeling conducted here excludes the catastrophic climate change (Weitzman 2009), potentially triggered by one or several of the earth's tipping elements.

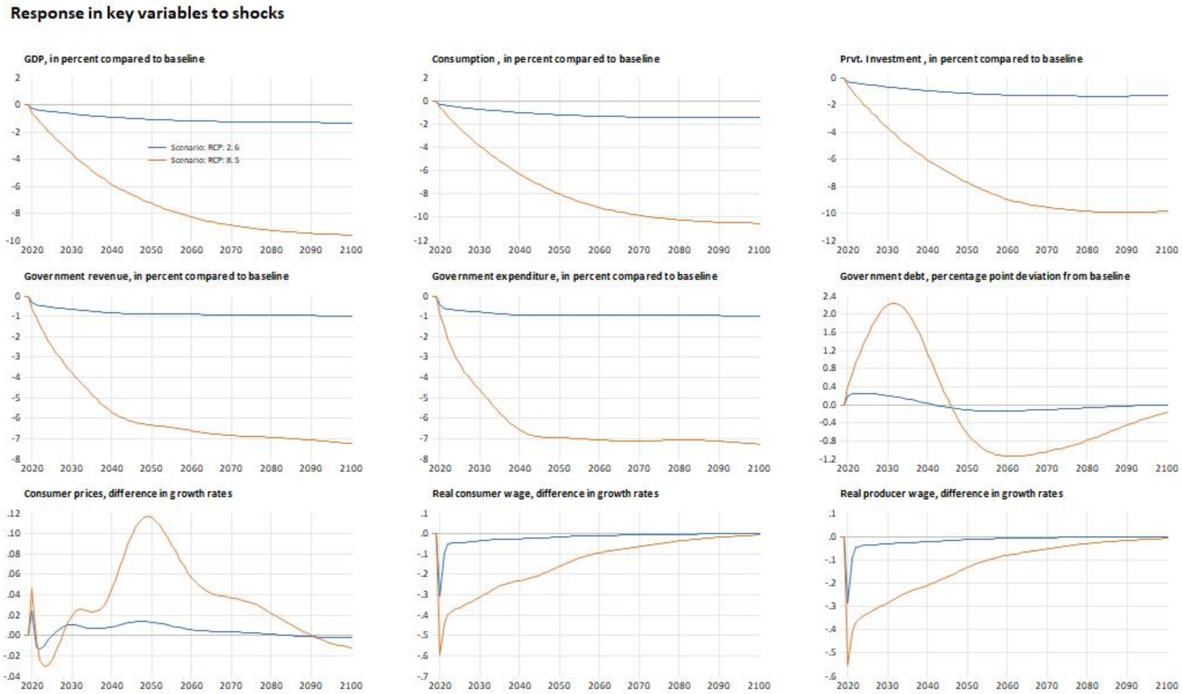


Figure 31: Economic effects of combined damages

## 4.3 Adaptation to climate change

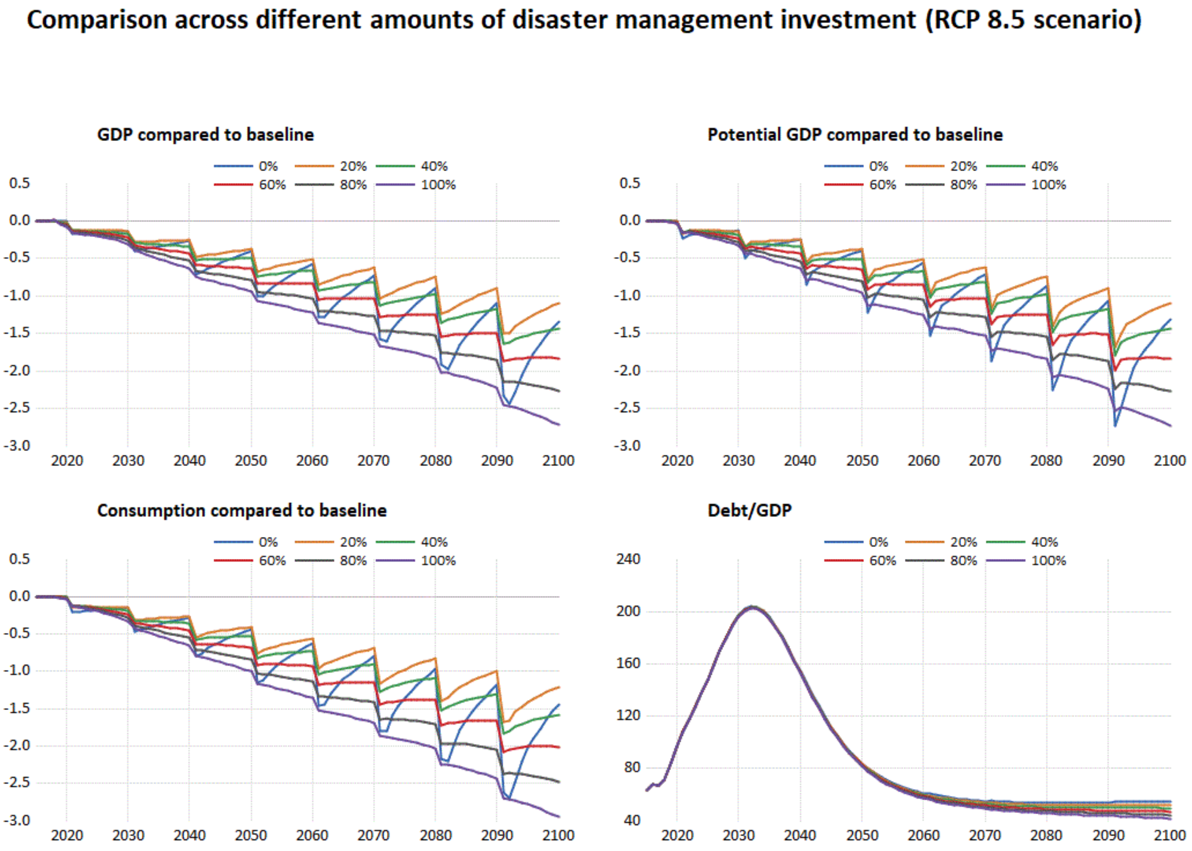
Given the non-linear model structure, the economywide response to adaptation investments depends importantly on the extent of the investments. Similarly, the long run impacts will depend on how they are paid for. To the extent that productive investment is forgone to pay for adaptation investment, the productive capital stock and therefore supply potential of the economy will suffer. These effects are important drivers of the results reported in the following simulations.

### 4.3.1 Impacts of adaptation investment to reduce the impact of flooding

The simulations reported in Figure 32 are somewhat artificial, they show the impact of a very large flood occurring at a regular once in 10 years frequency. The actual distribution of flooding, see Table 6, involves many smaller floods distributed more evenly across time. The illustrative shock is set equal to ten times the average annual flooding damage (for the RCP 8.5 scenario), occurring once every 10 years. The same set of floods were run under different adaptation investment regimes ranging from spending levels equal to 20% of the annual expected damage to 100%.

Figure 32 reports results for some key economic variables for each of these scenarios, with adaptation investment running from 0% of the expected value of damages (the BAU scenario) to 100% of the expected value of damages. Outcomes are presented for GDP, potential GDP, household consumption and the public debt to GDP ratio. In each case, outputs are expressed as a percent deviation from a baseline of a hypothetical version of the Pakistani economy that does not have flooding damages. The exception is the debt-to-GDP ratio, which is presented as the change in the debt-to-GDP ratio.

Figure 32: The effect macroeconomic effect of adaptation



The 0% line in Figure 32 shows the economic outcomes that can be expected without adaptation, as such, it represents the economic damages from flooding. Looking at the GDP figure, by 2100 aggregate GDP will be 1.4 percent lower due to capital destruction from repeated flooding. The 20, 40, 60, 80 and 100% lines illustrate the impact on the economy, when adaptation spending was set equal to those shares of the expected level of damages. Aggregate GDP losses (as compared with the no flood scenario) are smaller in the case of 20% and 40% adaptation than in the 0% scenario, are about equal on average in the 60% scenario and are higher in scenarios where spending on adaptation exceeds 60% of the expected flooding damages– although the path of all economic variables is smoother.

GDP outcomes decline as expenditure on adaptation rises, because the benefits of additional adaptation investments decline as the stock of adaptation capital rises, but the opportunity cost associated with financing additional investment stays broadly constant. In the scenarios of Figure 32, adaptation investment is financed by reducing government spending on productive investment, implying less productive capital and a decline in potential output (Panel 2 of Figure 32). The counterbalancing of this effect via reduced losses of physical capital from flooding is strongest at lower levels of adaptation investment. While the level effect of adaptation investment is negative for investments in excess of 60% of the expected value of damages, the degree of volatility of output continues to decline and is most easily observed in the attenuation of the post-flooding economic cycles at higher levels of adaptation investment.

At low rates of adaptation investment, the benefits of adaptation investment outweigh the opportunity costs coming from reduced government productive investment and other spending. However, as spending levels rise, the average benefit from adaptation declines due to the concave protection function, which means that the return on investment in adaptation capital declines at higher levels of investment. Thus at 20% of expected losses adaptation reduces GDP losses, while also reducing volatility. At 60% the GDP effect mainly disappears as the additional investment in adaptation capital are much less protective than the first and the crowding out of productive investment becomes a dominant effect on GDP. For investment rates higher than 60% of expected losses the crowding effect dominates, and GDP effects are worse than in the no investment scenario. Whether these results are welfare reducing will depend on the importance consumers attach to the smoother profile of GDP in the high adaptation investment scenarios.

# 5. Unmodeled aspects of climate economics

In addition to the modeling described in the previous sections, an important result of this project is the identification of aspects of climate change, which are important for an aggregate assessment of climate policy, but which could not be included. The unmodeled aspects refer to the macroeconomic modeling (Section 5.1), the impact of climate change (Sections 5.2 to 5.5), adaptation (Section 5.6) and mitigation (Section 5.7). The list is not exhaustive, of course. The effect of climate change on ecosystem services could also be included, for example.

## 5.1 Structural change

While other variants of the MFMod model consider time horizons of only a few years, this model considers a time horizon until 2100. This is necessary to see, for example, the impact of a given climate policy on long-term carbon emissions. In this long time horizon, however, it can be expected that the structure of Pakistan's economy changes. The share of the service sector, for example increases with development. Countries also shift from informal to formal employment as they develop. For increased accuracy, therefore, this structural change occurring in the baseline could be modeled more directly. This would require factor inputs at a sectoral level and a decomposition of productivity into within and between effects. Structural change would materialize as productive factors are allocated to more productive sectors. This would imply a shrinking of the agricultural sector and an increase in services. In PAKMod structural change arises due to shifts in demand for agricultural and industrial goods as well as demand for services.

Finally, it is not theoretically satisfying to model total labor as a CES aggregate of informal and formal labor. The CES function assumes that there is a complementarity between formal and informal labor. While this is a meaningful assumption for different types of labor, like skilled and unskilled labor, it is not meaningful for types of labor, which differ only by their legal status. A better alternative is the model described by (Ulyssea 2018), a simplified version of which is suggested in the appendix of the section.

## 5.2 Loss of human capital

There is evidence that both natural disasters and high temperature have negative effects on human capital. We present three channels for this link below, but there may well be additional channels.

### 5.2.1 Disaster effect on the human capital of adults

(Yagan 2019) shows that the 2007-2009 unemployment shock of the financial crisis reduced the employment rate in the US, while the unemployment rate returned to the pre-crisis level. This means that a considerable number of workers left the labor force. Testing several possible mechanisms for this effect, the author concludes that the exit from the labor market is caused by two effects: loss of human capital and lower labor demand. Three possible explanations for the reduction in labor demand are given, including productivity shocks. (Blanchard and Summers 1986) and (Reifschneider, Wascher, and Wilcox 2015) also point to a loss in human capital as the reason for permanent effects of an economic crisis.

### 5.2.2 Disaster effect on the human capital of children

Deuchert and Felfe (2015) show that disasters, super typhoons in this case, reduce children's education, but not their health. According to the authors this effect results from parents shifting their investments away from children's education. Rosales-Rueda (2018) shows that children who were affected by a natural disaster during pregnancy have lower cognitive outcomes because of decreased nutrition quality available to their mothers. Karbownik and Wray (2019) find that a disruption of health service after hurricanes in the US causes children to have a 5% lower income later in life.

### 5.2.3 Temperature effect on the human capital of children

Isen, Rossin-Slater and Walker (2017) and Fishman, Carrillo and Russ (2019) show that adults who had been exposed to higher temperature in utero have lower income. Isen, Rossin-Slater and Walker (2017) further show that access to air conditioning eliminates the effect almost completely, thus suggesting that the effect is caused directly by the temperature. Lloyd *et al.* (2019) describe a substantial increase of stunting among children due to climate change.

## 5.3 Effect on TFP

There is a large literature (Anzoategui et al. 2019; Benigno and Fornaro 2017; Huber 2018; Duval, Hong, and Timmer 2019; Queralto 2019; Bianchi, Kung, and Morales 2019) that suggests that a crisis reduces aggregate demand and that firms respond to this decrease in part by lowering their investments in research and development. When firms invest less in R&D, productivity growth slows for a period, and this reduces the level of GDP. While these papers consider financial or banking crises, it is plausible that large natural disasters cause a disruption of the financial sector and thus trigger the described reductions in R&D investments and therefore reduce the level of TFP.

## 5.4 Effect on investment

When disasters occur frequently, investors anticipate this and reduce the expected rate of return on investment. As a result, they invest less (Hsiang and Jina 2015). To the extent that the incidence of disasters is unchanged, this effect is included in PAKMod, because it is reflected in historical investment rates. However, if the incidence of disaster were to increase, the additional losses in the productivity of investment is not captured in the model. Introducing a forward-looking aspect into the investment decision, that explicitly incorporates the expected capital losses, would capture such an effect. When disasters occur very frequently, it becomes impossible for countries to maintain economic growth and a disaster-induced poverty trap results (Stéphane Hallegatte and Dumas 2009).

## 5.5 Uncertainty

The damage of climate change maybe grossly underestimated in this model. (Stern 2013) points out that catastrophic outcomes are typically not considered adequately in economic models. This is related to the argument of (Weitzman 2009) that there is a non-negligible risk of apocalyptic catastrophes (which would justify efforts to avoid climate change at all cost). The potential for these dramatic catastrophes is linked to the possibility that tipping points in the earth system triggering positive feedback loops of global heating (Lenton et al. 2008).

## 5.6 Adaptation

In modeling the effectiveness of adaptation, a key equation is the relation between adaptation capital and protection, $P = \gamma_1 \left(\frac{K^A}{K^{Amax}}\right)^{\gamma_2}$. While the functional form seems natural and has been used in the literature, the calibration of the parameters is very uncertain. Finding data on these parameters or estimating them would strengthen the modeling of adaptation strongly. This would have to be done for each of the modeled damages separately. A starting point could be chapter 17 of IPCC (2014a), which summarizes the state of knowledge on the “Economics of Adaptation”. A subchapter on “Costing

Adaptation" gives some indications on methodology but does not provide data that would be directly useful for calibrating the parameters of the protection function.

Further damages of relevance for Pakistan are extreme heat events, landslides, and droughts. For the first two of these, there seems to be hardly any data, although droughts are subsumed in the modeled loss of agricultural productivity.

### 5.7 Distributional aspects

The aggregate nature of PAKMod as a macroeconomic model, precludes consideration of the distributional aspects of climate policy and climate impacts. Climate policy is expected to have a regressive effect in developed countries and a progressive effect in most developing countries (Dorband et al. 2019; Metcalf 2019). Further, the revenue generated in carbon pricing can be used to address distributional effects directly (Klenert et al. 2018; Jakob et al. 2016). These are important aspects for the effect of climate policy on welfare, that could be addressed by pairing PAKMod with a microsimulation model such as the World Bank's Global Income Distribution Dynamics Model.[34]

In addition, natural disasters have a strong distributional effect and climate change is expected to increase the frequency of natural disasters. Low-income households have lower resilience to disaster shocks and are thus affected more strongly. The effect of climate change on poverty has been analyzed in Hallegatte *et al.* (2016) and Hallegatte and Rozenberg (2017). For both of these publications, a microsimulation model was used, for details see the "Supplementary Information" for Hallegatte and Rozenberg (2017). The data of the PAKMod model could be used as an input to the microsimulation model to analyze poverty effects.

Another way to estimate the distributional or welfare losses of climate-related natural disasters is the literature on the welfare implications of business cycles (Cho, Cooley, and Kim 2015; McKay and Reis 2016). The insights of this literature could be transferred to the business cycles caused by disasters.

## 6. Conclusion

This paper documents the practical aspects of integrating climate considerations into a macrostructural model of the type typically used in Ministries of Finance and Economy for forecasting, fiscal sustainability and policy analysis. Such a model can contribute importantly to mainstreaming climate considerations into the regular decision-making process of central economic ministries. Climate outputs, emissions, economic damages, and health impacts of pollution are standard outputs of the model and are presented on an equal footing against other policy priorities, such as unemployment, inflation, and fiscal and monetary sustainability. The model allows climate policy to be examined in an economy-wide context. Just as importantly, it allows the otherwise unanticipated climate effects of policies not directly aimed at climate to be considered.

Five separate climate modules are incorporated into to the World Bank model covering: 1) A more disaggregated energy module; 2) an energy emissions and pollution module; 3) damage functions that reflect the impact of a changing climate on the economy; 4) adaptation and capital protection functions

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[34] See for example https://web.worldbank.org/archive/website01589/WEB/IMAGES/PARAL-31.PDF

that reflect how investments can reduce the damages that might otherwise occur; and finally 5) informality.

The energy emissions and pollution modules help map out how economic activity affects the environment and climate, and can, in conjunction with different policy levers (including carbon taxes), be used to model various decarbonization strategies. Presented simulations are consistent with those from other climate models. Importantly, economic outcomes depend on what is done with tax revenues. Given the high degree of informality in the Pakistani economy, an approach that reduces taxes that are imposed on a narrower tax base (such as formal labor) could reverse the small negative impact of a carbon tax on GDP.

The modeling also served to highlight the economic consequences of climate change. Simulations based on a significant global warming (RCP 8.5) suggest that reduced labor and agricultural productivity, increased frequency of extreme weather events and higher pollution could combine to reduce GDP by more than 10 percent, as compared with a scenario where the climate did not continue warming or by 1.7 percent as compared to a scenario where additional climate change was limited (RCP 2.6).

The modeling of adaptation is more speculative, but suggests that in the face of a concave protection function the largest benefit from adaptation expenditures would be attained by a level of spending in the range of 25 to 30 percent of expected damages.

While many climate outcomes and considerations are included in this paper, some were excluded principally because of data limitations. These represent areas for further research, calling for empirical work to better understand the economic damages caused by climate change in various sectors through the factors of production and shifts in demand, but also to better quantify the economic benefits in terms of forgone damages accrued by adaptation investments.

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# Appendix

## New MFMod mnemonics

The energy module introduces some new mnemonics to MFMod. First, we introduce the physical quantities (QN), price index (XN), current price values (CN) and constant price values (KN) for production.

| **Model Mnemonic** | **Explanation** | **Unit** | **Variable name in paper** |
|---|---|---|---|
| PAKNVCOLPRODQN | Coal, production | ktoe | $Q_{coal,t}$ |
| PAKNVOILPRODQN | Oil, production | ktoe | $Q_{oil,t}$ |
| PAKNVGASPRODQN | Gas, production | ktoe | $Q_{gas,t}$ |
| PAKNVRENPRODQN | "Renewables", production | ktoe | $Q_{ren,t}$ |
| PAKNVCOLPRODXN | Coal, price deflator | (none) | $P^{XN}_{coal,t}$ |
| PAKNVOILPRODXN | Oil, price deflator | (none) | $P^{XN}_{oil,t}$ |
| PAKNVGASPRODXN | Gas, price deflator | (none) | $P^{XN}_{gas,t}$ |
| PAKNVRENPRODXN | "Renewables", price deflator | (none) | $P^{XN}_{ren,t}$ |
| PAKNVENGTOTLXN | Energy, price deflator | (none) | $P^{XN}_{E,t}$ |
| PAKNVCOLPRODCN | Coal production, current value | LCU mn | $Y^{CN}_{coal,t}$ |
| PAKNVOILPRODCN | Oil production, current value | LCU mn | $Y^{CN}_{oil,t}$ |
| PAKNVGASPRODCN | Gas production, current value | LCU mn | $Y^{CN}_{gas,t}$ |
| PAKNVRENPRODCN | "Renewables" production, value | LCU mn | $Y^{CN}_{ren,t}$ |

| | | | |
|---|---|---|---|
| PAKNVENGTOTLCN | Total energy production, current v. | LCU mn | $Y_{E,t}^{CN}$ |
| PAKNVCOLPRODKN | Coal production, constant value | LCU mn | $Y_{coal,t}^{KN}$ |
| PAKNVOILPRODKN | Oil production, constant value | LCU mn | $Y_{oil,t}^{KN}$ |
| PAKNVGASPRODKN | Gas production, constant value | LCU mn | $Y_{gas,t}^{KN}$ |
| PAKNVRENPRODKN | "Ren." production, constant value | LCU mn | $Y_{ren,t}^{KN}$ |
| PAKNVENGTOTLKN | Total energy production, constant v. | LCU mn | $Y_{E,t}^{KN}$ |

In creating these variables, we use some auxiliary variables which help align the data sources.

| **Mnemonic** | **Explanation** | **Unit** | **Variable** |
|---|---|---|---|
| PAKNVCOLPRODCN2 | Coal production, current value | LCU mn | $\hat{Y}_{coal,t}^{CN}$ |
| PAKNVOILPRODCN2 | Oil production, current value | LCU mn | $\hat{Y}_{oil,t}^{CN}$ |
| PAKNVGASPRODCN2 | Gas production, current value | LCU mn | $\hat{Y}_{gas,t}^{CN}$ |
| PAKNVRENPRODCN2 | "Renewables" production, value | LCU mn | $\hat{Y}_{ren,t}^{CN}$ |
| PAKNVCOLPRODKN2 | Coal production, constant value | LCU mn | $\hat{Y}^{KN}{}_{coal,t}$ |
| PAKNVOILPRODKN2 | Oil production, constant value | LCU mn | $\hat{Y}^{KN}{}_{oil,t}$ |
| PAKNVGASPRODKN2 | Gas production, constant value | LCU mn | $\hat{Y}^{KN}{}_{gas,t}$ |
| PAKNVRENPRODKN2 | "Ren." production, constant value | LCU mn | $\hat{Y}^{KN}{}_{ren,t}$ |
| SCALINGF | Scaling factor for energy (value) | (none) | $\gamma_t^{CN}$ |
| SCALINGFR | Scaling factor for energy (quantity) | (none) | $\gamma_t$ |

We repeat the first table, this time for imports. The price deflator for imports is the same as for production.

| **Mnemonic** | **Explanation** | **Unit** | **Variable** |
|---|---|---|---|
| PAKNVCOLNIMPQN | Coal, net import, quantity | ktoe | $Q_{coal,t}^{M}$ |
| PAKNVOILNIMPQN | Oil, net import, quantity | ktoe | $Q_{oil,t}^{M}$ |
| PAKNVGASNIMPQN | Gas, net import, quantity | ktoe | $Q_{gas,t}^{M}$ |
| PAKNVRENNIMPQN | "Renewables", net import, quantity | ktoe | $Q_{ren,t}^{M}$ |
| PAKNVCOLNIMPCN | Coal, net import, current value | LCU mn | $M_{coal,t}^{CN}$ |

| | | | |
|---|---|---|---|
| PAKNVOILNIMPCN | Oil, net import, current value | LCU mn | $M^{CN}_{oil,t}$ |
| PAKNVGASNIMPCN | Gas, net import, current value | LCU mn | $M^{CN}_{gas,t}$ |
| PAKNVRENNIMPCN | "Ren.", net import, current value | LCU mn | $M^{CN}_{ren,t}$ |
| PAKNVENGNIMPCN | Total net energy import, current v. | LCU mn | $M^{CN}_{E,t}$ |
| PAKNEIMPGSNECN | Non-energy imports, current value | LCU mn | $M^{CN}_{Oth,t}$ |
| PAKNVCOLNIMPKN | Coal, net import, constant value | LCU mn | $M^{KN}_{coal,t}$ |
| PAKNVOILNIMPKN | Oil, net import, constant value | LCU mn | $M^{KN}_{oil,t}$ |
| PAKNVGASNIMPKN | Gas, net import, constant value | LCU mn | $M^{KN}_{gas,t}$ |
| PAKNVRENNIMPKN | "Ren.", net import, constant value | LCU mn | $M^{KN}_{ren,t}$ |
| PAKNVENGNIMPKN | Total net energy import, constant v. | LCU mn | $M^{KN}_{E,t}$ |
| PAKNEIMPGSNEKN | Non-energy imports, constant value | LCU mn | $M^{KN}_{Oth,t}$ |
| PAKNVENGNIMPXN | Energy import deflator | (none) | $P^{M,XN}_{E,t}$ |
| PAKNEIMPGSNEXN | Non-energy imports, price deflator | (none) | $P^{M,XN}_{Oth,t}$ |

The table below lists all variables related to emissions.

| **Mnemonic** | **Explanation** | **Unit** | **Variable** |
|---|---|---|---|
| PAKGGREVCO2CER | Carbon tax on coal | USD/t | $\tau^{coal}_{t}$ |
| PAKGGREVCO2OER | Carbon tax on oil | USD/t | $\tau^{oil}_{t}$ |
| PAKGGREVCO2GER | Carbon tax on gas | USD/t | $\tau^{gas}_{t}$ |
| WLDFCOAL_AUS* | World coal price | USD/mt | $P^{USD}_{coal,t}$ |
| WLDFCRUDE_PETRO* | World oil price | USD/BBL | $P^{USD}_{oil,t}$ |
| WLDFNGAS_EUR* | World gas price | USD/MMBTU | $P^{USD}_{gas,t}$ |
| WLDHYDROPOWER | World bioenergy price | USD/kWh | $P^{USD}_{ren,t}$ |
| CONVMTTOE | Conversion toe to mt | mt/toe | $\beta^{coal}$ |
| CONVBBLTOE | Conversion toe to BBL | BBL/toe | $\beta^{oil}$ |
| CONVMMBTUTOE | Conversion toe to mmbtu | mmbtu/toe | $\beta^{gas}$ |
| CONVKWHTOE | Conversion toe to kWh | kWh/toe | $\beta^{ren}$ |

|  |  |  |  |
|---|---|---|---|
| PAKNVCOLPRODGN | Coal, gross price deflator | (none) | $\bar{P}^{index}_{coal,t}$ |
| PAKNVOILPRODGN | Oil, gross price deflator | (none) | $\bar{P}^{index}_{oil,t}$ |
| PAKNVGASPRODGN | Gas, gross price deflator | (none) | $\bar{P}^{index}_{gas,t}$ |
| PAKNECONENGYGN | Total energy, gross price deflator | (none) | $\bar{P}^{index}_{E,t}$ |
| EMISCOAL | Emission intensity coal | t/toe | $\alpha^{coal}$ |
| EMISOIL | Emission intensity oil | t/toe | $\alpha^{oil}$ |
| EMISGAS | Emission intensity gas | t/toe | $\alpha^{gas}$ |
| PAKCCEMISCO2CKN | Emissions from coal | t | $EM_{coal,t}$ |
| PAKCCEMISCO2OKN | Emissions from oil | t | $EM_{oil,t}$ |
| PAKCCEMISCO2GKN | Emissions from gas | t | $EM_{gas,t}$ |
| PAKCCEMISCO2TKN | Emissions from all sources | t | $EM_{tot,t}$ |
| PAKGGREVEMISCN | Revenue from CO2 tax | LCU mn | $Rev_t$ |

*) Mnemonics already exists in MFMod glossary.

The table below lists all variables related to consumption.

| **Mnemonic** | **Explanation** | **Unit** | **Variable** |
|---|---|---|---|
| PAKNECONENGYKN | Total energy consumption, constant | LCU mn | $C^{KN}_{E,t}$ |
| PAKNECONENGYCN | Total energy consumption, current | LCU mn | $C^{CN}_{E,t}$ |
| PAKNECONENGYXN | Total energy consumption, deflator | LCU mn | $P^{C,XN}_{E,t}$ |
| PAKNECONOTHRKN | Total other consumption, constant | LCU mn | $C^{KN}_{oth,t}$ |
| PAKNECONOTHRCN | Total other consumption, current | LCU mn | $C^{CN}_{oth,t}$ |
| PAKNECONOTHRXN | Total other consumption, deflator | LCU mn | $P^{C,XN}_{Oth,t}$ |
| PAKNECONENGYSH | Consumption weight, energy | LCU mn | $\omega^{Con}_{E}$ |
| PAKNECONOTHRSH | Consumption weight, other | LCU mn | $\omega^{Con}_{Oth}$ |

The table below contains the parameters introduced here.

| **Mnemonic** | **Explanation** | **Variable** | **Calibration** |
|---|---|---|---|
| PAKCESENGYPROD | Substitution elasticity, production | $\sigma^{Prod}$ | 1.05 |

| | | | |
|---|---|---|---|
| PAKCESENGYIMP | Substitution elasticity, energy imports | $\sigma^{Imp}$ | 1.05 |
| PAKCESENGYCON | Substitution elasticity, consumption | $\sigma^{Con}$ | 1.05 |
| PAKCESENGYIMPT | Substitution elasticity, energy and other | $\sigma^{ImpT}$ | 1.05 |
| PAKNVCOLPRODSH | Share of coal in energy production | $\omega_{col}^{Prod}$ | (endogenous) |
| PAKNVOILPRODSH | Share of oil in energy production | $\omega_{oil}^{Prod}$ | (endogenous) |
| PAKNVGASPRODSH | Share of gas in energy production | $\omega_{gas}^{Prod}$ | (endogenous) |
| PAKNVRENPRODSH | Share of renewables in energy production | $\omega_{ren}^{Prod}$ | (endogenous) |
| PAKNVCOLNIMPSH | Share of coal in energy imports | $\omega_{col}^{Imp}$ | (endogenous) |
| PAKNVOILNIMPSH | Share of oil in energy imports | $\omega_{oil}^{Imp}$ | (endogenous) |
| PAKNVGASNIMPSH | Share of gas in energy imports | $\omega_{gas}^{Imp}$ | (endogenous) |
| PAKNVRENNIMPSH | Share of renewables in energy imports | $\omega_{ren}^{Imp}$ | (endogenous) |
| PAKNEIMPENGYSH | Share of energy in total imports | $\omega_{E}^{Imp}$ | (endogenous) |
| PAKNEIMPOTHRSH | Share of other imports in total imports | $\omega_{Oth}^{Imp}$ | (endogenous) |

## Appendix 1A: The informal labor market with heterogeneous firms

In this appendix, we present a micro-founded model of the endogenous decision between working in the formal or informal market. The model is a simplified version of the model presented in (Ulyssea 2018). We follow the paper in the basic structure: There are separate profit functions for the formal and informal sectors and firms decide endogenously how to operate (and if to operate or not). As a model exclusively dedicated to informality, the paper goes further into detail, in particular to explain the intensive margin (informal employment in the formal sector) and the productivity overlap of formal and informal firms. We abstract from these finer points.

### The production function

We assume that firms can choose freely whether to produce in the formal or informal sector. Depending on the choice, firms employ a sector specific productivity multiplier $\eta_F$ or $\eta_I$ with $\eta_F > \eta_I$. This represents that firms in the formal sector can produce more efficiently as they have access to financial services, the countries' legal system and other benefits.

We consider that firm productivity is exogenous, following (Hopenhayn 1992) and (Melitz 2003) on firm heterogeneity like. Every firm thus has a firm-specific productivity $\theta$. In a first simplified approach, we assume that firms employ only labor (this can be generalized later). There is a decreasing return to labor with exponent $0 < \alpha < 1$. Taken together, the firm production function is

$$y_i = \eta_i \theta l^{\alpha}.$$

## Profit maximization

Running the firm requires an annual fixed cost of $f_i, i \in \{F, I\}$. Complying with regulation as a formal firm generates an additional fixed cost so that $f_F > f_I$. In addition, the firm pays the market wage $w$ for labor and taxes with $\tau_F > \tau_I = 0$. Defining the output price as $p$, profits are given as

$$\Pi_\mathrm{i}(l) = py - (w + \tau_i)l - f_i.$$

Maximizing profits yields that the optimal labor employment is

$$l_i^* = \left(\frac{p\eta_i\theta\alpha}{w + \tau_i}\right)^{\frac{1}{1-\alpha}}.$$

For a given $i \in \{F, I\}$, this optimal labor choice has very intuitive implications: The optimal labor choice depends positively on $p$, $\eta_i$ and $\theta$ and negatively on $w$ and $\tau_i$.

The optimal output of a firm with productivity $\theta$ in sector $i$ is thus

$$y_i^*(\theta) = \eta_i\theta(l_i^*)^\alpha = (\eta_i\theta)^{\frac{1}{1-\alpha}}\left(\frac{p\alpha}{w + \tau_i}\right)^{\frac{\alpha}{1-\alpha}}.$$

## Activity choice

In the literature on firm productivity, firms come into existence with a randomly drawn level of productivity. This can be seen as the skill of the entrepreneur, which is revealed once the entrepreneur has started his/her business. Based on the productivity the firm has, it decides between three activities: (i) leave the market, because the productivity is so low that no profits can be made, (ii) produce in the informal sector, or (iii) produce in the formal sector.

In order to start producing, the firm needs to make at least zero profit in the informal sector,

$$\Pi_I(l_I^*) = 0.$$

$$\Leftrightarrow p\eta_I\theta\left(\frac{p\eta_I\theta\alpha}{w + \tau_I}\right)^{\frac{\alpha}{1-\alpha}} - (w + \tau_I)\left(\frac{p\eta_I\theta\alpha}{w + \tau_I}\right)^{\frac{1}{1-\alpha}} - f_I = 0$$

$$\Leftrightarrow \frac{(p\eta_I\theta)^{\frac{1}{1-\alpha}}}{(w + \tau_I)^{\frac{\alpha}{1-\alpha}}}\alpha^{\frac{\alpha}{1-\alpha}} - \frac{(p\eta_I\theta)^{\frac{1}{1-\alpha}}}{(w + \tau_I)^{\frac{\alpha}{1-\alpha}}}\alpha^{\frac{1}{1-\alpha}} - f_I = 0$$

$$\Leftrightarrow \theta^{\frac{1}{1-\alpha}}\frac{(p\eta_I)^{\frac{1}{1-\alpha}}}{(w)^{\frac{\alpha}{1-\alpha}}}\tilde{\alpha} - f_I = 0$$

$$\Leftrightarrow \theta^{\frac{1}{1-\alpha}} = \frac{f_I}{\tilde{\alpha}}\frac{(w)^{\frac{\alpha}{1-\alpha}}}{(p\eta_I)^{\frac{1}{1-\alpha}}}$$

$$\Leftrightarrow \theta^I = \left(\frac{f_I}{\tilde{\alpha}}\right)^{1-\alpha}\frac{w^\alpha}{p\eta_I}$$

We used $\tilde{\alpha} = \alpha^{\frac{\alpha}{1-\alpha}} - \alpha^{\frac{1}{1-\alpha}}$ to shorten notation. The level $\theta^I$ is the minimum required for a firm to stay in the informal market.

### Choosing formality or informality

Low-productivity firms will opt to stay in in the informal sector. The reason is that they produce at a small scale, so that it does not pay off to pay the fixed cost of entering the formal sector. High-productivity firms make this investment. The threshold level can be determined by setting profits under optimal labor input equal:

$$\Pi_F(l_F^*) = \Pi_I(l_I^*)$$

$$\Leftrightarrow p\eta_F\theta\left(\frac{p\eta_F\theta\alpha}{w+\tau_F}\right)^{\frac{\alpha}{1-\alpha}} - (w+\tau_F)\left(\frac{p\eta_F\theta\alpha}{w+\tau_F}\right)^{\frac{1}{1-\alpha}} - f_F = p\eta_I\theta\left(\frac{p\eta_I\theta\alpha}{w}\right)^{\frac{\alpha}{1-\alpha}} - (w)\left(\frac{p\eta_I\theta\alpha}{w}\right)^{\frac{1}{1-\alpha}} - f_I$$

$$\Leftrightarrow \frac{(p\eta_F\theta)^{\frac{1}{1-\alpha}}}{(w+\tau_F)^{\frac{\alpha}{1-\alpha}}}\alpha^{\frac{\alpha}{1-\alpha}} - \frac{(p\eta_F\theta)^{\frac{1}{1-\alpha}}}{(w+\tau_F)^{\frac{\alpha}{1-\alpha}}}\alpha^{\frac{1}{1-\alpha}} - f_F = \frac{(p\eta_I\theta)^{\frac{1}{1-\alpha}}}{(w)^{\frac{\alpha}{1-\alpha}}}\alpha^{\frac{\alpha}{1-\alpha}} - \frac{(p\eta_I\theta)^{\frac{1}{1-\alpha}}}{(w)^{\frac{\alpha}{1-\alpha}}}\alpha^{\frac{1}{1-\alpha}} - f_I$$

$$\Leftrightarrow \theta^{\frac{1}{1-\alpha}}\frac{(p\eta_F)^{\frac{1}{1-\alpha}}}{(w+\tau_F)^{\frac{\alpha}{1-\alpha}}}\tilde{\alpha} - f_F = \theta^{\frac{1}{1-\alpha}}\frac{(p\eta_I)^{\frac{1}{1-\alpha}}}{(w)^{\frac{\alpha}{1-\alpha}}}\tilde{\alpha} - f_I$$

$$\Leftrightarrow \theta^{\frac{1}{1-\alpha}}p^{\frac{1}{1-\alpha}}\tilde{\alpha}\left(\frac{(\eta_F)^{\frac{1}{1-\alpha}}}{(w+\tau_F)^{\frac{\alpha}{1-\alpha}}} - \frac{(\eta_I)^{\frac{1}{1-\alpha}}}{(w)^{\frac{\alpha}{1-\alpha}}}\right) = f_F - f_I$$

$$\Leftrightarrow \theta^{\frac{1}{1-\alpha}} = \frac{1}{p^{\frac{1}{1-\alpha}}\tilde{\alpha}}\frac{f_F - f_I}{\left(\frac{(\eta_F)^{\frac{1}{1-\alpha}}}{(w+\tau_F)^{\frac{\alpha}{1-\alpha}}} - \frac{(\eta_I)^{\frac{1}{1-\alpha}}}{(w)^{\frac{\alpha}{1-\alpha}}}\right)}$$

$$\Leftrightarrow \theta' = \frac{1}{p}\left(\frac{1}{\tilde{\alpha}}\frac{f_F - f_I}{\left(\frac{(\eta_F)^{\frac{1}{1-\alpha}}}{(w+\tau_F)^{\frac{\alpha}{1-\alpha}}} - \frac{(\eta_I)^{\frac{1}{1-\alpha}}}{(w)^{\frac{\alpha}{1-\alpha}}}\right)}\right)^{1-\alpha}$$

Firms with a productivity below $\theta^F$ will produce in the informal market, firms with a higher productivity will produce in the formal market. This result is again very intuitive: The threshold $\theta^F$ depends positively on the fixed cost of producing in the formal sector $f_F$, and on the productivity in the informal sector $\eta_I$. It depends negatively on the fixed cost of producing in the informal sector $f_I$ and the productivity in the formal sector $\eta_F$. Most importantly for us, the threshold depends positively on labor taxes,

$$\frac{d\theta'}{d\tau_F} > 0.$$

This means that a decrease in taxes on formal labor will decrease the threshold between the informal and the formal sector, so that the most productive informal firms move to the formal sector.

The condition under which $\theta^F \geq \theta^I$, that is for which both formal and informal markets exist, is given by:

$$\theta^{'} \geq \theta^{I} \quad iff \quad \left(1-\frac{f_F}{f_I}\right) \geq 1-\left(\frac{\eta_F}{\eta_I}\left(\frac{w}{w+\tau_F}\right)^{\alpha}\right)^{\frac{1}{1-\alpha}}$$

The profit functions and thresholds are illustrated in Figure 33. Figure 34 shows the effect of a decrease in labor taxes. A decrease of labor taxes decreases the cost in the formal sector and thus shifts the profit curve upwards.

Figure 33: Model equilibrium for sector choice

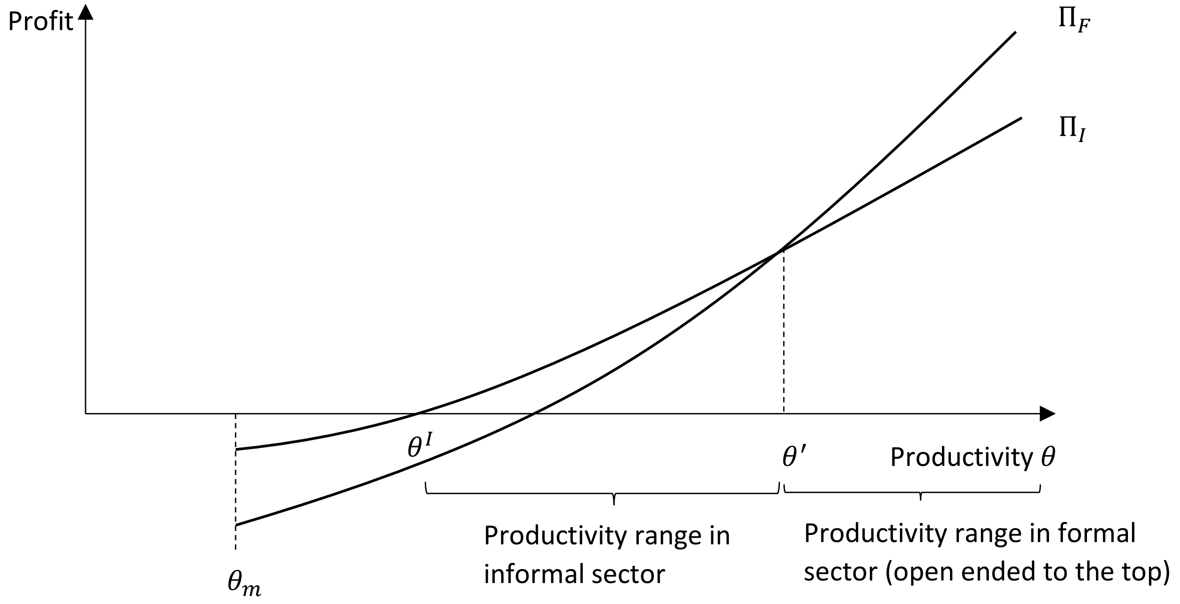
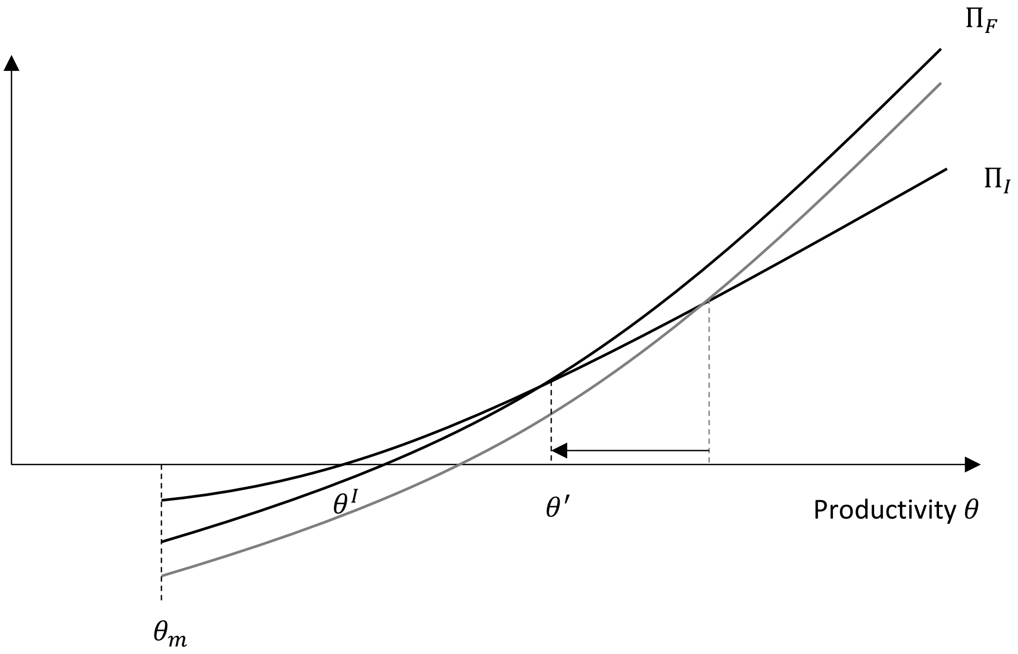


Figure 34: Effect of a decrease in labor taxes



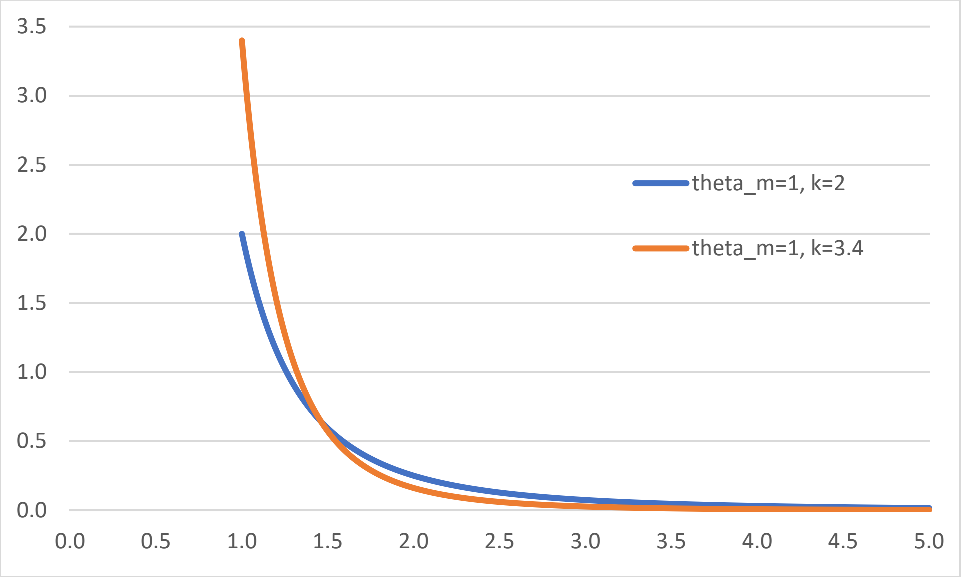
### The probability distribution

In the heterogeneous firm literature, firms enter the market, then randomly draw a level of productivity. Based on the observed distribution of the productivity of firms, (Ghironi and Melitz 2005) assume that productivity draws are given by a Pareto distribution,

$$g(\theta) = k\frac{(\theta_m)^k}{\theta^{k+1}},$$

where $\theta_m$ is the minimum of productivity draws. We assume that $k > \frac{1}{1-\alpha}$ to ensure that the variance of firm size is finite. The Pareto distribution is illustrated in Figure 35.

Figure 35: An illustration of the Pareto distribution



Once firms have drawn a productivity, they chose whether to stay in the market or leave. As we have seen above, firms with a productivity $\theta < \theta^I$ leave the market. The probability density function of firms in the market is thus given by

$$\hat{g}(\theta) = \frac{1}{1 - G(\theta^I)} k \frac{(\theta_m)^k}{\theta^{k+1}}, for\ \theta > \theta^I$$

Where $G(\theta)$ is the cumulative distribution function of the Pareto distribution, so that $G(\theta') = \int_{\theta_m}^{\theta^I} k \frac{(\theta_m)^k}{\theta^{k+1}} d\theta = 1 - \left(\frac{\theta_m}{\theta^I}\right)^k$.

## Total output

Total outputs in the informal sector, the formal sector and from all firms are thus given by:

$$Y_I = \int_{\theta^I}^{\theta'} y_I^*(\theta)\hat{g}(\theta) d\theta$$

$$= \int_{\theta^I}^{\theta'} (\eta_I \theta)^{\frac{1}{1-\alpha}} \left(\frac{p\alpha}{w}\right)^{\frac{\alpha}{1-\alpha}} \frac{1}{1 - G(\theta^I)} k \frac{(\theta_m)^k}{\theta^{k+1}} d\theta$$

$$= (\eta_I)^{\frac{1}{1-\alpha}} \left(\frac{p\alpha}{w}\right)^{\frac{\alpha}{1-\alpha}} \frac{1}{1 - G(\theta^I)} k (\theta_m)^k \int_{\theta^I}^{\theta'} \theta^{\frac{1}{1-\alpha} - k - 1} d\theta$$

$$= (\eta_I)^{\frac{1}{1-\alpha}} \left(\frac{p\alpha}{w}\right)^{\frac{\alpha}{1-\alpha}} \frac{1}{1 - G(\theta^I)} k (\theta_m)^k \left| \frac{1}{\frac{1}{1-\alpha} - k} \theta^{\frac{1}{1-\alpha} - k} \right|_{\theta^I}^{\theta'}$$

$$= (\eta_I)^{\frac{1}{1-\alpha}} \left(\frac{p\alpha}{w}\right)^{\frac{\alpha}{1-\alpha}} \frac{1}{1-G(\theta^I)} k(\theta_m)^k \frac{1}{\frac{1}{1-\alpha}-k} \left(\theta'^{\frac{1}{1-\alpha}-k} - \theta^{I\frac{1}{1-\alpha}-k}\right),$$

$$Y_F = \int_{\theta'}^{\infty} y_F^*(\theta)\hat{g}(\theta)d\theta$$

$$= (\eta_F)^{\frac{1}{1-\alpha}} \left(\frac{p\alpha}{w+\tau_F}\right)^{\frac{\alpha}{1-\alpha}} \frac{1}{1-G(\theta^I)} k(\theta_m)^k \frac{1}{\frac{1}{1-\alpha}-k} \left(-\theta'^{\frac{1}{1-\alpha}-k}\right),$$

$$Y = Y_I + Y_F.$$

Notice that the condition $k > \frac{1}{1-\alpha}$ ensures $\lim_{\theta\to\infty} \theta^{\frac{1}{1-\alpha}-k} = 0$, so that the upper limit of the integral for the formal sector vanishes.

## Calibration

Calibrating the model parameters is not straightforward, as they cannot be observed directly. Table 8 provides some parameters chosen in the literature.

Table 8: Parameter values for informality from the literature

| **Paper** | **(Ghironi and Melitz 2005)** | **(Khan and Khan 2011)** | **(Ulyssea 2018)** |
|---|---|---|---|
| **Relevant pages** | **885** | **15** | **2033** |
| $\boldsymbol{\eta_F}$ | n/a | 1* | n/a** |
| $\boldsymbol{\eta_I}$ | n/a | 0.4* | n/a** |
| $\boldsymbol{f_F}$ | (calibrated rel. to $f\_I$) | | 0.5w*** |
| $\boldsymbol{f_I}$ | 1 (normalization) | | 0.258w*** |
| $\boldsymbol{\theta_m}$ | 1 | | 7.7 |
| $\boldsymbol{k}$ | 3.4 | | 3.08 |
| $\boldsymbol{\alpha}$ | n/a | | 0.605 |

*) These values do not correspond directly to the $\eta_i$ in our model. The measure average productivity in the sectors, which in our case is given by $\hat{\eta}_F = \eta_F \int_{\theta''}^{\infty} \theta * \hat{g}(\theta)\, d\theta$ and $\hat{\eta}_I = \eta_I \int_{\theta'}^{\theta''} \theta * \hat{g}(\theta)\, d\theta$.

**) Instead of different productivity levels, this model uses a risk of being detected and punished for informal employment, given by $\tau_i(l_i)$.

***) The parameters $f_i$in our model correspond to $c_s = \gamma_s w_2$, see page 2030. The values for $\gamma_s$ are the one given in the table of parameters on page 2033.

The numerical application of the existence condition for both the informal and informal markets (see above) is verified with this standard calibration (including for ranges of $\tau_F = 0\ to\ w$, ie. 100 % tax rate on wages).

## Appendix 2A: Estimating structural unemployment

Estimating the structural unemployment rate is hard and is driven by theoretical assumptions. The existence of a natural rate of unemployment is assumed on the basis of various real rigidities (search and match) (Pissarides 2000; Daly et al. 2012), efficiency wages (Shapiro and Stiglitz 1984), minimum wages

(Fields 1997), and labor union pressure (Pissarides 1986; Johnson and Layard 1986). For a useful empirical method based on a wage Phillips curve relationship, see (Blanchard and Katz 1999).

The approach used in this model is based on distortions in prices and wages as well as taxes.

Assume that the production is generated by labor $(N)$ and TFP $(A)$ (capital is assumed to equal unity):

$$Y_i = AN_i^{1-\alpha}$$

where $1-\alpha$ is the labor income share.

The marginal product of labor is:

$$MPL_i = (1-\alpha)AN_i^{-\alpha}$$

The firm produces differentiated goods as above and demand for each good is:

$$Y_i = D(P_i) = \left(\frac{P_i}{P}\right)^{-\sigma}\frac{Y}{n}$$

Marginal revenue can be calculated from total revenue $(TR_i = P_iY_i)$:

$$MR_i = \frac{dTR_i}{dY_i} = P_i + Y_i\frac{dP_i}{dY_i} = P_i\left(1+\frac{dP_i}{dY_i}\frac{Y_i}{P_i}\right) = P_i\left(1-\frac{1}{\sigma}\right)$$

This firm will expand output up until marginal revenue equals marginal costs (in this case the MPL):

$$MC_i = \frac{W_i}{MPL_i}$$

$$P_i\left(\frac{\sigma-1}{\sigma}\right) = \frac{W_i}{(1-\alpha)AN_i^{-\alpha}}$$

$$P_i = \left(\frac{\sigma}{\sigma-1}\right)\frac{W_i}{(1-\alpha)AN_i^{-\alpha}} = m^p\frac{W_i}{(1-\alpha)AN_i^{-\alpha}}$$

This standard equation suggests that prices are a markup over marginal costs.

Next, we derive the employment needed to produce output. First divide the price of each good by the aggregate price:

$$\frac{P_i}{P} = \frac{m^p}{P}\frac{W_i}{(1-\alpha)AN_i^{-\alpha}}$$

Insert the equation above into the demand equation:

$$Y_i = \left(\frac{m^p}{P}\frac{W_i}{(1-\alpha)AN_i^{-\alpha}}\right)^{-\sigma}\frac{Y}{n}$$

Insert this equation into the production function and solve for employment:

$$Y_i = AN_i^{1-\alpha} \Rightarrow N_i = \left(\frac{Y_i}{A}\right)^{\frac{1}{1-\alpha}}$$

$$N_i = \left(\frac{\left(\frac{m^p}{P}\frac{W_i}{(1-\alpha)AN_i^{-\alpha}}\right)^{-\sigma}\frac{Y}{n}}{A}\right)^{\frac{1}{1-\alpha}}$$

$$N_i = \left(\frac{W_i}{P}\right)^{\frac{-\sigma}{1+\alpha(\sigma-1)}}\left(\frac{Y}{nA}\right)^{\frac{1}{1+\alpha(\sigma-1)}}\left(\frac{(1-\alpha)A}{m^p}\right)^{\frac{\sigma}{1+\alpha(\sigma-1)}}$$

Next, we derive the union's objective function which is to maximize the income of its members by either choosing wages or labor. Note that the union makes its decision after receiving wage signals from the employer:

$$\Gamma(w_i) = (1-\tau)(w_i - b)N_i(w_i)^{\zeta}$$

where $\zeta$ is a parameter that weights the union's objective of either achieving a higher wage for its members or higher employment.

The union will attempt to set the wage to maximize the utility function taking the firm's labor demand decision into account:

$$\frac{\partial\Gamma(w_i)}{\partial w_i} = N_i^{\zeta} + (1-\tau)(w_i - b)\zeta N_i^{\zeta-1}\left(\frac{\partial L_i}{\partial w_i}\right) = 0$$

$$1 + \frac{(1-\tau)(w_i - b)\zeta}{w_i}\left(\frac{\partial N_i}{\partial w_i}\frac{w_i}{N_i}\right) \Rightarrow w_i = \frac{(1-\tau)\zeta\varepsilon}{(1-\tau)\zeta\varepsilon - 1}b$$

Or in nominal terms indexed to expected prices:

$$w_i = \frac{(1-\tau)\zeta\varepsilon}{(1-\tau)\zeta\varepsilon - 1}b * P^e = m^w * b * P^e$$

This implies that under a dominant union, there will be a markup over the expected price. This markup is a function of taxes and the elasticity of labor demand $\frac{\partial N_i}{\partial w_i}\frac{w_i}{N_i} = \varepsilon$.

Substituting the real wage into the labor input schedule:

$$N_i = \left(\frac{Y}{nA}\right)^{\frac{1}{1+\alpha(\sigma-1)}} \left(\frac{(1-\alpha)A}{m^p m^w * b}\frac{P}{P^e}\right)^{\frac{\sigma}{1+\alpha(\sigma-1)}}$$

Total employment is $N = nN_i$ and using $Y = nY_i = nBN_i^{1-\alpha}$

$$N = n\left(\frac{(1-\alpha)A}{m^p m^w * b}\frac{P}{P^e}\right)^{\frac{1}{\alpha}}$$

The natural rate of employment in equilibrium (when prices equal expectations):

$$N^* = n\left(\frac{(1-\alpha)A}{m^p m^w * b}\right)^{\frac{1}{\alpha}}$$

Or we can write the natural unemployment level as:

$$U^* = (1 - N^*)LF$$

Or in terms of a rate:

$$u^* = (1 - N^*) = 1 - \left(\frac{(1-\alpha)A}{m^p m^w * b}\right)^{\frac{1}{\alpha}}$$

$$u^* = 1 - \left(\frac{(1-\alpha)A}{\left(\frac{\sigma}{\sigma-1}\right)\left(\frac{(1-\tau)\zeta\varepsilon}{(1-\tau)\zeta\varepsilon-1}\right) * b}\right)^{\frac{1}{\alpha}}$$

The natural rate of unemployment is a function of TFP, taxes, price markup (determined by the price elasticity of demand), the weight unions place on wages over employment, the labor demand elasticity, the labor income elasticity and the non-labor income.

Note that the labor demand elasticity is pinned down by the income share and elasticity of substitution for goods:

$$\varepsilon = \frac{\sigma}{1+\alpha(\sigma-1)}$$

**A note on calibration**

Note that if the price elasticity of demand tends to infinity ($\sigma \to \infty$) then the price markup tends to 1 where prices equal marginal cost.

Our model for estimating the markup is:

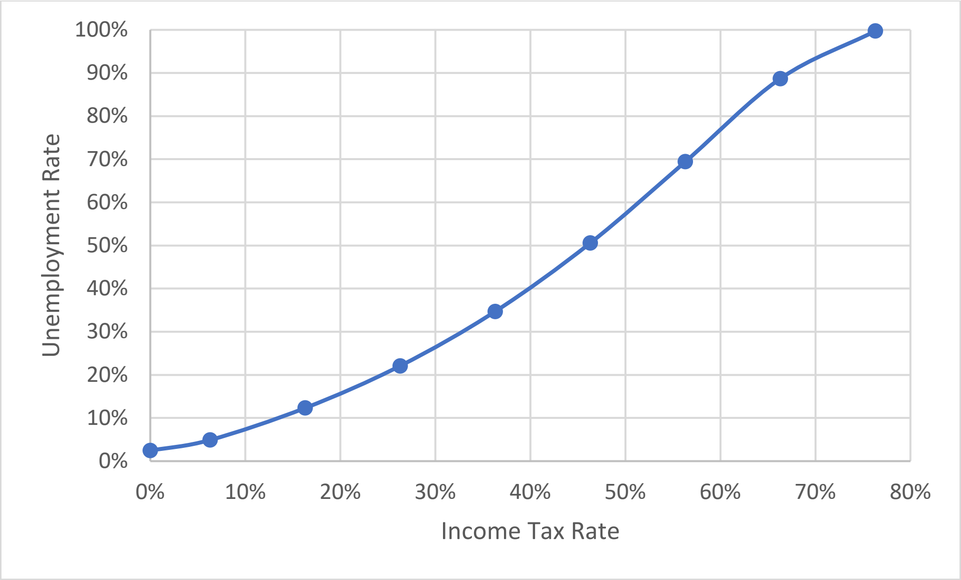
$$\Delta\left(p_t^{fcst}\right) = \beta_1 + \theta\left[p_{t-1}^{fcst} - \beta_2 mc_t\right] + \beta_3 ygap_t + \sum_{i=0} \beta_i \Delta p_{t-1-i}^{fcst} + \sum_{i=0} \gamma_i \Delta mc_{t-i} + \varepsilon_t^p$$

The markup is calculated as: $e^{\left(\frac{\beta_1}{\theta}-1\right)} \approx 25\%$. This implies that $\left(\frac{\sigma}{\sigma-1}\right) = 0.25 \Rightarrow \sigma(1-1.25) = -1.25 \Rightarrow \sigma = 5$

The labor share in income is $(1-\alpha) = 0.65$. The replacement ratio is assumed to be $b = 0.75$ while the average effective income tax rate is equal to $\tau = 5\%$. Note that a positive markup requires $\zeta\varepsilon > 1$. The formula above suggests that $\varepsilon = 2.61$. It is hard to pin down the union preference of employment over higher wages. In the model it is calibrated to equal $\zeta = 2$. This gives a structural unemployment rate of 4%, very close to the average unemployment rate of 3.57% historically.

Figure 36 below plots the unemployment rate for different tax rates and with the parameters described above. A higher tax wedge has a nonlinear impact on structural unemployment. Higher tax rates increase unemployment monotonically.

Figure 36: The relationship between income tax rates and the unemployment rate



Source: Own calculations

## Appendix 3A: Different kinds of adaptation in Pakistan

### *Adaptation to heat stress*

(Runhaar et al. 2012) identify several possible measures for adapting to the effect of heat stress on humans. They include various approaches for reducing indoor temperature, adjusting city planning to reduce heat (through open water, for example) and disaster contingency plans. (Krayenhoff et al. 2018) mention evaporative roofs, street trees and lightweight urban materials as the most promising approaches for reducing heat in cities. (Aflaki et al. 2017) highlight the potential of green roofs and green facades as adaptation to heat.

Additional studies consider the role of natural spaces, mostly parks and lakes in cities. (Meerow and Newell 2017) propose a model to design green infrastructure in a way that optimizes several benefits for the population, including urban heat island amelioration. (W. Zhou, Wang, and Cadenasso 2017) point out the benefits of trees on temperature in cities, but also highlight the importance of site-specific planning.

In addition to modifications in buildings and cities, some studies highlight the potential of preparing emergency response centers and the general population for extreme heat. (Harlan and Ruddell 2011) and (Zuo et al. 2015) point to heat warning systems for triggering emergency responses as possibly the most beneficial policy.

Some of these studies provide some empirical estimates. (Krayenhoff et al. 2018) and (Aflaki et al. 2017) for example indicate by how much their proposed measures can reduce temperature. Combined with the link of temperature to productivity loss, this could be an avenue for estimating a cost benefit analysis. However, the cost of the measures is not specified, and the data are limited to cities.

### *Adaptation to flooding*

Some studies focus on identifying the measures available for adapting to river floods. In a review article, (Olmstead 2014) mentions flood barriers, green infrastructure (parks), protection of facilities like wastewater treatment plants, enhancement of groundwater recharge, reservoir storage capacity and relocating existing infrastructure to higher ground as options for adapting to floods. In a case study for the Netherlands, (Tol et al. 2003) find that embankments can reduce the annual average damage from river floods by over 90% and nature development and deepening the river bed can reduce damages by 60% or more.

Two studies provide some form of quantifying river flood adaptation measures. (Jongman et al. 2015) show that vulnerability to river floods has decreased between 1980 and 2010 and that future increases in risk can be contained with disaster risk reduction strategies. (Willner et al. 2018) provide a calculation of the adaptation level needed to keep flood risk at present levels. They identify Pakistan as one of the countries most affected by flood risk.

There is also research on floods and adaptation by Pakistani researchers, mostly published in national journals. However, they do not provide a quantification and mostly detail the benefits of one or a few adaptation options. According to (Memon and Sharjeel 2016) improved weather forecasting would be a low-cost, but effective way to reduce the impact of floods. (Abbas et al. 2016) compare Pakistan to India and Nepal and find that flood management planning is performing much less well in Pakistan than in the South Asian neighbors. (Qasim et al. 2017) recommend the more flood-secure housing construction with more durable material and in safer locations. (Aslam 2018) identify river embankments and water storage reservoirs as already existing adaptation options and further point to several non-structure measures, including an early warning system.

Given the methodology and the level of detail, (Willner et al. 2018) seem to have data which could allow for calibrating an adaptation function for flood risk. However, the data in the paper is not sufficient and the “level of protection” would still need to be linked to expenditure.

### *Adaptation to agricultural damage*

There is much more literature specific to Pakistan or adaptation in agriculture than for adaptation to floods and heat stress. However, the focus is on adaptation done privately by farmers. As mentioned before, the private adaptation efforts are already considered in our data on impacts of climate change in agriculture, because the impacts are calculated net of adaptation efforts. According to (Ali and Erenstein 2017), the most important adaptation measures by farmers in Pakistan are adjustment in sowing time, use of drought relevant crops and shifting to new crops. (Abid et al. 2015) further add planting of shade trees and changing fertilizers.

According to (Ali and Erenstein 2017) options for the government to enhance adaptation are subsidies/taxes and improvements in agricultural markets. (Abid et al. 2016) name provision of infrastructure as well as access to inputs, markets and information services as measure the government could take to facilitate adaptation by farmers. (Gorst, Dehlavi, and Groom 2018) name providing access to credit and agricultural extension (training of farmers) as further fields of government activity.

To summarize, the role of the government in adaptation to the impacts of climate change on agriculture seems to concern mostly the improvement of services and institutional functioning. The infrastructure investments suggested by (Abid et al. 2015) refer in particular to transport infrastructure, which would not only have a role for adaptation, but also for productivity more generally. Further, we could not find any approach to quantifying the link between government investment in agriculture and avoided damages.

## Appendix 4A: Simulations using an alternative renewable price assumption

This section presents simulations using an alternative baseline for renewable prices and hence a slower baseline transition to renewables and higher baseline emissions from hydrocarbons. In addition, these scenarios also assume large fixed costs in transitioning – thus halting the degree of stranding assets when renewable prices fall.

Figure 37 shows that baseline emissions continue to grow relative to 2017. The growth in emissions follow economic growth (see bottom right panel). A large and increasing carbon tax reduces emissions significantly, but does not lead to full decarbonization. The emissions intensity, however, falls drastically over the period. The share of renewables in the economy, however, is still rising over the projection period (with positive slope). This implies that the economy will eventually decarbonize, but not necessarily within the projection frame. These results point to the importance of setting baselines robustly. There is significant uncertainty about the extent of technological change in both renewable and hydrocarbon innovations.

Figure 37: Emissions – baseline vs. carbon tax with different fiscal policies