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Public finance and climate change adaptation: could adaptation policies foster public fiscal sustainability? The case of Italy

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SUMMARY This paper analyses the link between adaptation investment against flooding and how it affects the public budget and its sustainability in the medium run. In particular, this assessment addresses the issue of how investing in climate change adaptation is sustainable for the public finance and how climate change related investment could foster economic growth and lowers public fiscal indicators, such as deficit/GDP and debt/GDP ratios. This preliminary work considers the case of Italy where flood risk is particularly high combined with a high level of deficit which is often considered as one of the limiting factor against new investment. Using a CGE model, we argue that introducing adaptation investments has a positive effect on fiscal indicators respect to an "inaction" scenario. Moreover, the positive effect is even higher when these adaptation investments are anticipatory.

Keywords: Computable general equilibrium, public investment, adaptation, deficit, debt

JEL Classification: C68, H54, H68

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INTRODUCTION

While the impacts of climate change on the productive structure of the economies is a well-established theme, climate change impacts on public budget was not considered until 2003 when Heller (Heller, 2003) defined climate change (together with demographic changes, and globalization) as one of the major threats posed on public budget in the future decades and as one of the main channels of very long- term challenge. The effects of climate change are two-fold: on the revenue and on the expenditure side.

In the context of climate change and adaptation policies, CEPS and ZEW (2010) distinguished two types of related fiscal costs named as “direct”, and “indirect”. The former include the construction and maintenance of protective infrastructures, the additional maintenance costs of public infrastructures affected by climate change, changes in social expenditures due to climate change impacts on employment and public health from potential repercussions on employment or alterations in health expenditures. Moreover, they consider as a particular kind of direct cost the revenue change effect. It is the change in revenues in the public budget due to shifts in the productive patterns and trade structure as well as in consumption. The indirect fiscal costs, instead, consider climate change impacts on fiscal capacity to deal with very long-term challenges.

Climate change will have direct impacts on the public finances that tend to amplify the wider challenges it poses. Global warming induces both slow moving, sector-specific productivity changes (e.g. a reduction in agricultural productivity) and the risk of more intense shocks (i.e. extreme events). Countries heavily dependent on few climate sensitive productive sectors may face significant revenue reductions. Public spending may be increased, for instance, by intensified incidence of vector borne diseases, or by new population movements. The importance (and sign) of these fiscal impacts will vary across countries, but they are likely to be most adverse precisely where vulnerabilities to climate change are greatest (IMF, 2008).

Until recently, a close connection between climate policies and public budgets was recognized mainly to mitigation whose implementation instruments are typically taxes/subsidies, directly linked to fiscal impacts. Today however, a similar relevance characterizes also adaptation requiring increased public expenditure, both on climate related public goods (such as information acquisition and dissemination on likely extreme events) and to protect other public expenditure “items” like, transportation systems, infrastructures, water and health systems. Against this background, adaptation to climate change might be essentially seen as an additional burden for public finances, however several studies highlight low cost/benefit ratio for many adaptation measures. On this basis, Ekins and Speck (2011) for instance, suggest that the final fiscal effect of adaptation is not completely negative: its protective effect on the whole economy could increase tax revenues when impacts occur and counterbalance the expenditure needed. However, the final net effect depends both on the structure of the tax system and the adaptation investment amount. CEPs and ZEW (2010) acknowledge the same uncertainty in the final fiscal outcome of adaptation, mainly because of the contextual existence of different types of adaptation responses, i.e. autonomous private adaptation, and public planned adaptation. Finally, Osberghaus and Reif (2010) highlight that the final sign of adaptation on the public budgets is not clear. Compared with a no adaptation scenario it can be obviously positive as long as it produces net benefits (in the form of reduced or avoided damages) and thus it increases the total economy's productivity. In practice, given the high uncertainty of future climate impacts the total budgetary effects of adaptation may also be negative. This is the case of adaptation to sea level rise where the construction of dikes is highly expensive and eventually after the construction the sea-level does not rise to the expected extent.

This paper aims to explore these issues respect to the specific case of Italy and flooding events. Italy appears particularly impacted by flooding. As the 2015 update of the report on hydro-geological risk in Italy (Trigila et al., 2015), at least 18% of the national territory is exposed to hydrological or geological risk, affecting 88% of the Italian municipalities. In the period 2010-2014, there were 145 deaths and 44528 people displaced due to floods and severe weather related events. Almost all Italian provinces (97 over a total of 110) were affected. Flood events usually affect more densely populated areas. Viable solutions to reduce risk and damage include lowering levels of exposure and vulnerability with a combination of structural and non-structural prevention measurements. Most of them require high level of investment in protective infrastructure.

As known, the Maastricht rules impose constraints on the expenditures level of EU governments and Mediterranean countries, such as Italy, France, Spain, Portugal and Greece, appear particularly vulnerable in their fiscal position. In this paper we try to demonstrate that even in case of tight budgetary constraints increasing climate change adaptation investment (in this case against flooding) can be a winning strategy also under the perspective of public budget sustainability.

The paper is structured as follows. Section 1 briefly review literature on flood impacts and related adaptation analysis using Computable General Equilibrium models. Section 2 concentrates on theoretical aspects to implement impacts and adaptation inside the ICES-XPS model. Then, section 3 describes the modeling set up with a focus on input data, aggregation and scenarios examined. Section 4 illustrates the results for Italy and briefly compares them with that of other European countries. Finally, section 5 concludes.

1. LITERATURE REVIEW

Computable General equilibrium (CGE) modeling is a well-established instrument to assess the indirect costs of climate change. As such, it has been also applied to the economic assessment of floods in many EU research initiatives and FP7 research projects (e.g. PESETA (Ciscar et al. 2012), PESETA II (Ciscar et al. 2014), ClimateCost (Bosello et al. 2012), McCallum et al. (2013)) and studies (Carrera et al. 2014). CGE models represent explicitly market interactions between sectors and regions (inter industry and international trade flows are accounted for by databases relying upon input-output Social Accounting Matrices). This allows tracing adjustment mechanisms in the whole economic system triggered by a “shock” initially concerning just one part of it (region or sector). In other words, not only direct costs, but also higher-order effects can be determined.

Biophysical impacts of river floods are introduced in CGE model in different ways. The PESETA and PESETA II projects consider on one hand the negative effect on residential buildings which leads to a higher private consumption forced to restore damaged building, on the other hand a loss in capital stock. The former negatively affects the welfare level while the latter affects capital accumulation and economic growth (Ciscar et al., 2012; Ciscar et al., 2014). The ClimateCost project (Bosello et al., 2012), suggests instead that floods affect negatively the agricultural sector via a reduction in land stock, other sectors (such as the residential or transport sector) via a reduction in sectoral capital productivity and labour productivity due to people displacement.

This paper addresses public planned adaptation therefore, similarly to Ciscar et al. (2012), flood protection expenditure is modelled as a forced demand increase toward the construction sector. However, differently from Ciscar et al. (2012), the demand stems from the public sector and not from the private household.

2. MODELLING FRAMEWORK

For this assessment, we use an extended version of the ICES recursive dynamic computable general equilibrium model (Eboli et al., 2010; Parrado and De Cian, 2014) enriched with a more realistic description of the public sector in order to better capture the relations between public expenditure in adaptation and public budget sustainability (Delpiazzo et al., forthcoming). The model is calibrated on the GTAP database version 8 (Narayanan et al. 2012).

Differently from the original ICES model in which the government ultimately behaves as the representative household, in the ICES-eXtended Public Sector (ICES-XPS) version, the government is a separate actor with its own budget constraint . Furthermore, the model now

includes different transfers between the government and households such as social transfers, and interest payments on debt stock. There are also transfers among governments in the form of international aid. Thus, government income is used for consumption, transfers, and savings. At the regional level, investments are function of private and public investments with a Cobb-Douglas formulation. The gap between public savings and public investments represent the government's financial needs (borrowing). This gap is financed by private households' savings, that could be both domestic and foreign. Investment is internationally mobile and regional savings (private plus public) from all regions are initially pooled and then redistributed to countries in order to equalize expected rates of return to capital in the long-run.
Accordingly, savings and investments are equalized at the world, but not at the regional level. Imbalances are "closed" by a surplus/deficit in foreign transactions (considered as the sum of trade surpluses/deficits and the net inflows of international transfers). In this context, government borrowing reduces the availability of regional savings with a consequent increase in saving prices which are negatively correlated to the rate of return to capital.

1) *Impacts and adaptation modeling in the ICES-XPS model*

Here, impacts are considered as an increase in total government expenditure ($QGOV_r$) and as a sector specific (i.e. construction sector) government expenditures ($QG_{CNST,r}$). Therefore, the government spends its income in goods and services in all sectors while for the construction sector there is an additional shock ($\Delta QG_{CNST,r}$) which is exactly the amount of expenditures the government face to restore damaged infrastructures affected by flooding. Formally, total government expenditures are:

$$PGOV_r \cdot QGOV_r = \sum_i PG_{i,r} \cdot QG_{i,r} \qquad (32)$$

In the construction sector (*i* = CNST), the demand is equal to:

$$PG_{CNST,r} \cdot QG_{CNST,r} = PG_{CNST,r} \cdot QG_{CNST,r} + \Delta QG_{CNST,r} \qquad (33)$$

Conversely, in the other sectors (*i* ≠ CNST):

$$PG_{i,r} \cdot QG_{i,r} = PG_{i,r} \cdot QG_{i,r} \cdot (1 - gcns_r) \qquad (34)$$

Where $gcns_r$ is a shifting parameter for expenditures in sectors *i* different from "construction" which ensures to respect the budget constraint for each year:

$$YG_r = \sum_i PG_{i,r} \cdot QG_{i,r} + QSAV\_GOV_r \cdot PSAVE_r \qquad (35)$$

Formally, $gcns_r$ is defined as:

$$gcns_r = \frac{\Delta QG_{CNST,r}}{PGOV_r \cdot QGOV_r - PG_{CNST,r} \cdot QG_{CNST,r}} \quad (36)$$

When the government decides to spend for adaptation we introduce planned adaptation as an increase in public investment which in turn diverts private investment.

Formally, regional investment net of depreciation ($NETINV_r$) is split into public ($GOVINV_r$) and private investments ($PRIVINV_r$) according to fixed shares:

$$NETINV_r = GOVINV_r + PRIVINV_r \quad (37)$$

Where: $GOVINV_r = \varepsilon_r \cdot NETINV_r$ and $PRIVINV_r = (1 - \varepsilon_r) \cdot NETINV_r$

Introducing additional adaptation infrastructure investments $\Delta GOVINV_{CNST,r}$ we change the share ε_r, which now is defined as $\varepsilon_{1,r}$:

$$\varepsilon_{1,r} = \frac{\Delta GOVINV_{CNST,r} + GOVINV_r}{NETINV_r} \quad (38)$$

While private investment adjusts so that its share on total regional depreciated investment is $(1 - \varepsilon_{1r})$.

Whenever adaptation investments do not completely eliminate impacts, residual damages are modeled as impacts.

3. EXPERIMENT SET-UP

Table 1 summarizes ICES-XPS model regional and sectoral aggregation used for this analysis. It disentangles Italy together with some other EU Mediterranean countries characterized by high level of public deficits and debts compared with the Maastricht criteria[1].

Table 1: Regional and Sectoral aggregation in the ICESXPS model

Regional Aggregation	**Sectoral Aggregation**
Italy	*Primary sector:*
France	Agriculture;
Greece	*Energy sector:*
Spain	Coal, Oil, Gas, Oil products;
Portugal	*Electricity sector:*
Rest of EU	Renewable electricity, Electricity from Fossil Fuels;
Rest of World	*Secondary sector and services:*

[1] In the exercise, France is included as, during the European Sovereign-Debt crisis, many analysts emphasized the quick deterioration of its public finance indicators.

	Energy intensive industries, Other industry and services, Construction, Public services.

1) Scenarios

To perform this analysis and consider the fiscal effect of adaptation policies against flooding, 3 scenarios are considered:

1. **Reference scenario.** It sets up how the economy grows in the timeframe 2007-2030. Specifically, growth rates for population and GDP are those of the OECD projections (Dellink et al., 2015) for the SSP2 scenario (IIASA,2016).
2. **"No Adaptation" scenario (No-Ad).** In this scenario the European countries are affected by floods and therefore their governments have to spend to rebuild affected infrastructures. In this case we want to assess the costs of the impacts in terms of GDP and their effects on the public budget, with a specific focus on deficit/GDP and debt/GDP ratios.
3. **Planned Adaptation scenario (Ad).** In this scenario governments concentrate in the 2008-2012 period river flood prevention expenditure and are thus able to reduce their (reactive) spending in restoration thereafter.

2) Input data

Data on climate change impacts and adaptation investments for river floods protection are based on results from the LISFLOOD model (Dankers and Feyen, 2008). This is a spatially distributed hydrological model embedded within a GIS environment. It simulates river discharges in drainage basins as a function of spatial information on topography, soils, land cover, and precipitation. This model has been developed for operational flood forecasting at the European scale and it is a combination of a grid-based water balance model and a 1-dimensional hydrodynamic channel flow routing model. The LISFLOOD model can assess the economic loss in the EU27 countries per different macro-sectors.

Table 2 summarizes the input data for all regions and countries considered. As already said the LISFLOOD hydrogeological model is an European one and gives results for the EU27, therefore impacts and adaptation expenditure for the rest of the ICES-XPS regions are not available. Therefore they are assumed to be null for the Rest of the World aggreate.

Table 2: Cumulated costs of flooding (column A) and cumulated residual impacts (B) and adaptation investments (C) in 2030

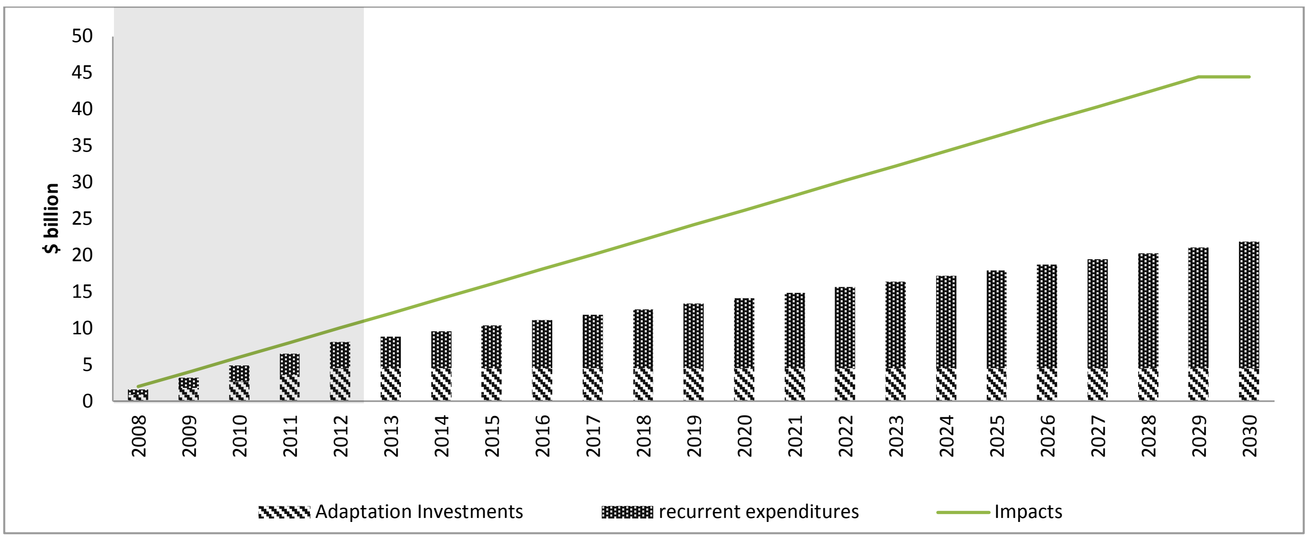
	No-Ad scenario	**Ad-Scenario**	
	(A)	**(B)**	**(C)**
	Recurrent expenditures	Recurrent expenditures	Adaptation investments
Italy	33.2	17.3	4.5
France	56.8	34.0	7.2
Greece	1.7	1.0	0.2

Spain	10.1	6.4	1.0
Portugal	0.4	0.3	0.02
Rest of EU	197.5	118.6	22.9

Note: numbers are 2007 dollar billion

Figure 1 shows the values of the input data for the ICES-XPS model for Italy in the "no adaptation" and the "adaptation" scenarios. The green line represents the cumulated costs in the No-Ad scenario, while the bars represent the cumulated adaptation expenditure and the recurrent expenditure needed to face the residual impacts which cannot be totally eliminated by adaptation. The shaded area represents the period when adaptation investments are concentrated.

Figure 1: cumulated impact, anticipatory adaptation and rehabilitating expenditure for Italy in the No-Ad and Ad scenarios



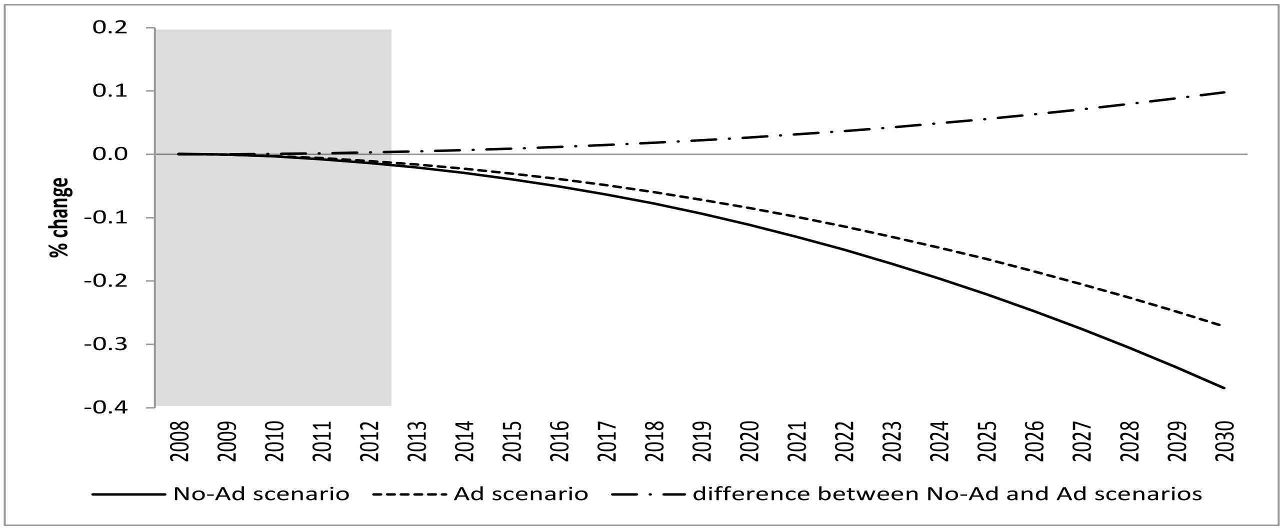
4. RESULTS

This section is divided into two parts. In the first one, we focus on the Italian situation; in the second one, we extend the analysis to the other EU countries to evaluate the robustness of the Italian outcome.

1) The Italian case

Figure 2 depicts the Italian GDP trends in the simulations. Both in the Ad and No-Ad scenarios the GDP is lower than in the reference. However, when adaptation takes place the GDP reduction in 2030 is nearly 30% lower. This suggests that adaptation investments have "protective" effect on the economic structure.

Figure 2: GDP percentage change in the No-Ad and Ad scenarios wrt reference



Source: ICES-XPS model

It is worth recalling that in the present exercise, GDP effects are not driven by loss (or avoided loss) of primary factors of production like land, capital and labour, or changes in their productivity, but by different patterns of public expenditure triggered by the presence (or absence) of adaptation. Bearing this in mind, the macroeconomics behind this results is strictly connected with the public saving-investment balance inside the country. When floods occur without adaptation, the government increases its recurrent expenditures to rehabilitate damaged infrastructures. In our assumption other public investments and recurrent expenditures remains fixed, which means that additional adaptation expenditure is financed by private savings borrowed at a positive interest by the government. This entails two negative effects: (i) a reduction in total savings and less investment in the current year, and (ii) a reduction in the following year due to the higher level of interest to be paid for the higher public borrowing from households.

The saving-investment unbalance impacts the trade balance as well. In the case of Italy, the trade balance worsens featuring an evident fall in exports while imports stay roughly constant.

In the Ad scenario, there is a lower level of residual impacts which sustains a higher level of national savings, investment and growth, and a lower worsening of the trade balance (Table 3).

Table 3: the saving- investment components in Italy in the No-Ad and Ad scenarios in 2030

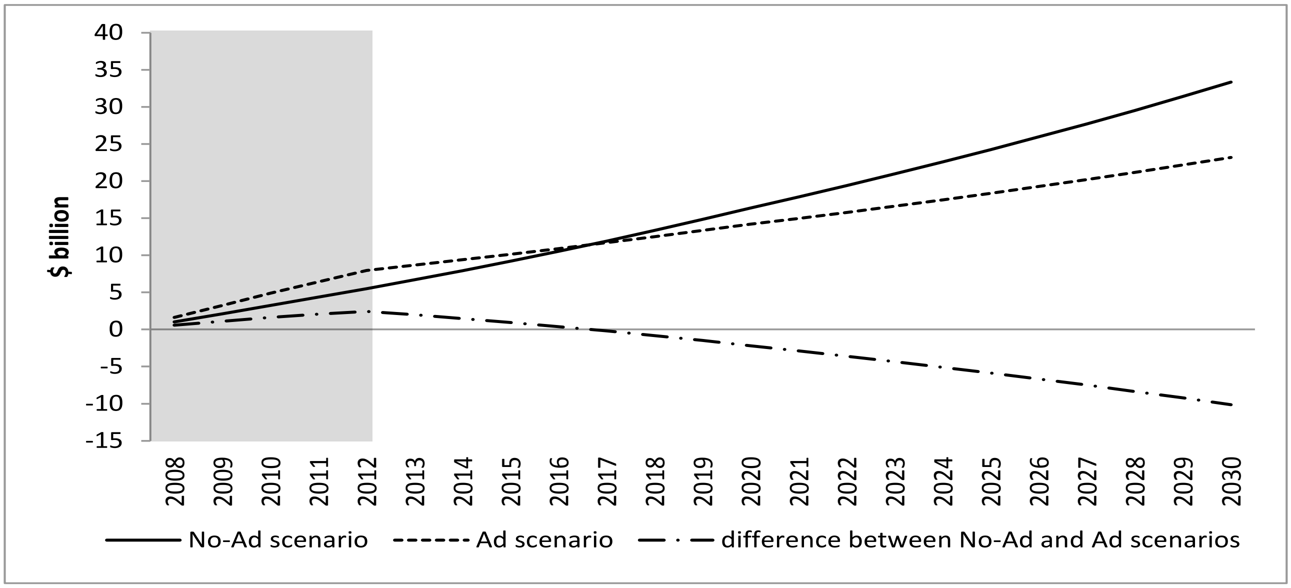
	No-Ad scenario	**Ad scenario**
	% change	% change
Regional savings	-26.63	-15.96
Private savings	0.11	0.07
Government savings	-56.64	-33.96
Investments	-2.21	-1.54
Imports	0.29	0.03
Exports	-4.04	-2.21

Note: percentage change with respect to 2030 in the reference scenario

Source:ICES-XPS model

Now we focus on the fiscal effect of the two scenarios. In the No-Ad and Ad scenario, tax revenues increase in nominal terms due to a higher price of capital that is accumulating at a slower pace than in the reference. However this increase, $ 4.8 and $ 2 billion in 2030 in the No-Ad and Ad scenarios respectively, is small compared with total government expenditures. Accordingly, public deficit is increasing in both scenarios, but with different patterns (Figure 2). While without adaptation, deficit increases more or less steadily along the whole simulation period, with adaptation, it increases more steeply until 2017, when adaptation expenditure is concentrated, then still increases, but at a slower pace. As a consequence, initially deficit is higher in the Ad than in the no Ad scenario until 2017 with the gap among the two widening until 2012 ($ 2.45 billion), then declining and reaching zero in 2017. Afterwards, deficit in the Ad scenario is lower than that of the No-ad scenario (with a gap of $ -10.13 billion in 2030).

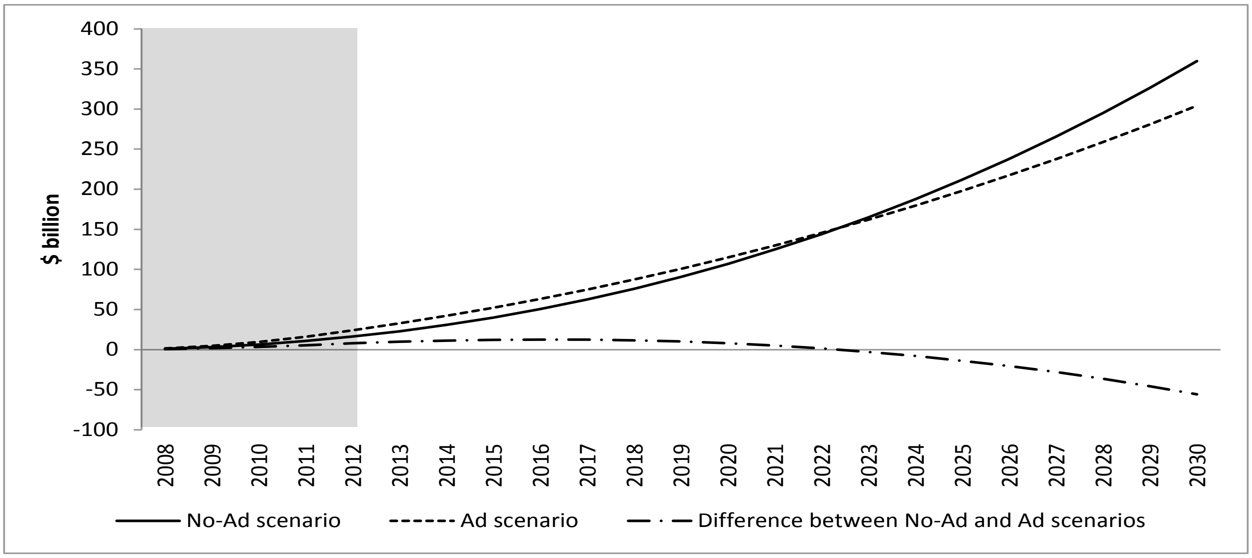
Figure2: change in public deficit in the No-Ad and Ad scenarios wrt reference



Source:ICES-XPS model

As public debt stock is the result of the accumulation process of yearly public deficit, a similar paths can be identified for debt, although with a 4 year time lag. Indeed, according to Figure 3, the stock of debt differential between the two scenario reaches its maximum ($ 12.59 billion) in 2016 while the two debt stock trends intersect between 2022/2023. In 2030 the differential in public debt stock between No-Ad and Ad scenarios is $ 55.79 billion.

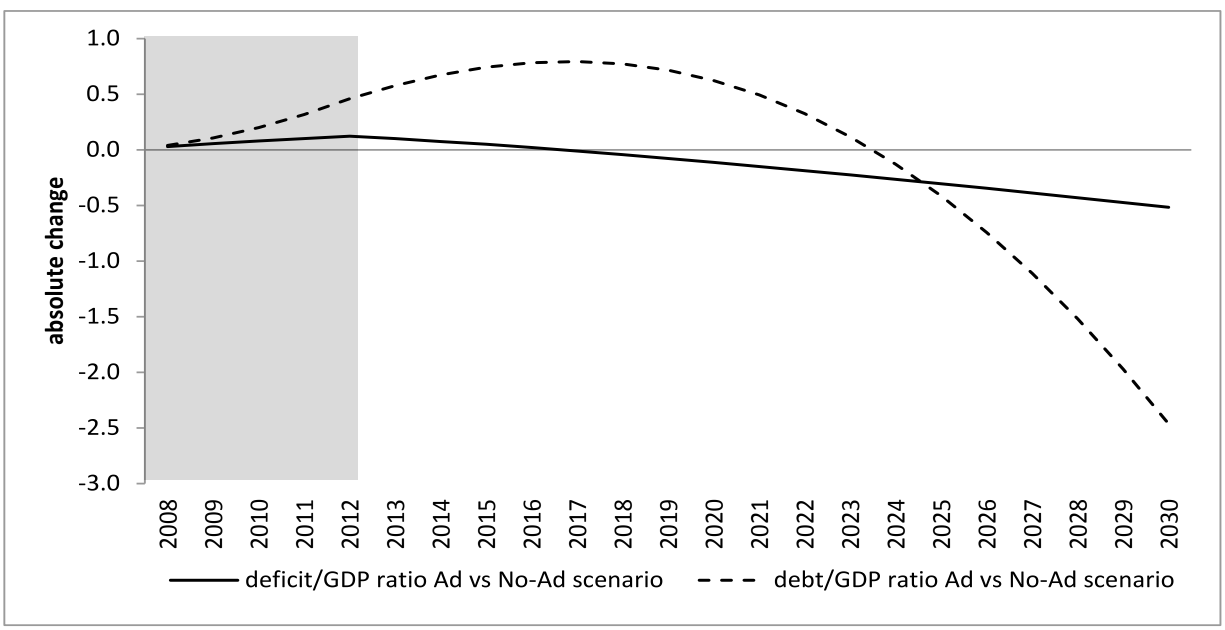
Figure 3: change in public debt stock in the No-Ad and Ad scenarios wrt reference



Source: ICES-XPS model

Finally, it can be interesting to analyze the trend in the deficit/GDP and debt/GDP ratios, which are commonly used as two measures of the sustainability of the public finance in the economy.

Figure 4: deficit/GDP and debt/GDP ratios in the Ad scenario wrt No-Ad scenario



Source: ICES-XPS model

Figure 4 shows positive feedback of climate change adaptation expenditure (in this case against flooding) on the fiscal position of Italy. Adaptation costs in terms of deficit/GDP ratio 0.12 percentage point in 2012 respect to no adaptation, while in terms of debt/GDP ratio it costs nearly 1 percentage point. However, in the medium run these ratios decline with gain in 2030 of 0.52 percentage points in deficit/GDP ratio and 2.46 percentage points in debt/GDP ratio. This suggests that although deficit and debt increase, the “protective” effect of adaptation on the productive side of the economy, captured by the real GDP variable, is positive and could increase the relative sustainability of public expenditure.

2) *The other EU countries*

Similar conclusions can be derived for the other EU countries scrutinized (Table 4 and Figure 5).

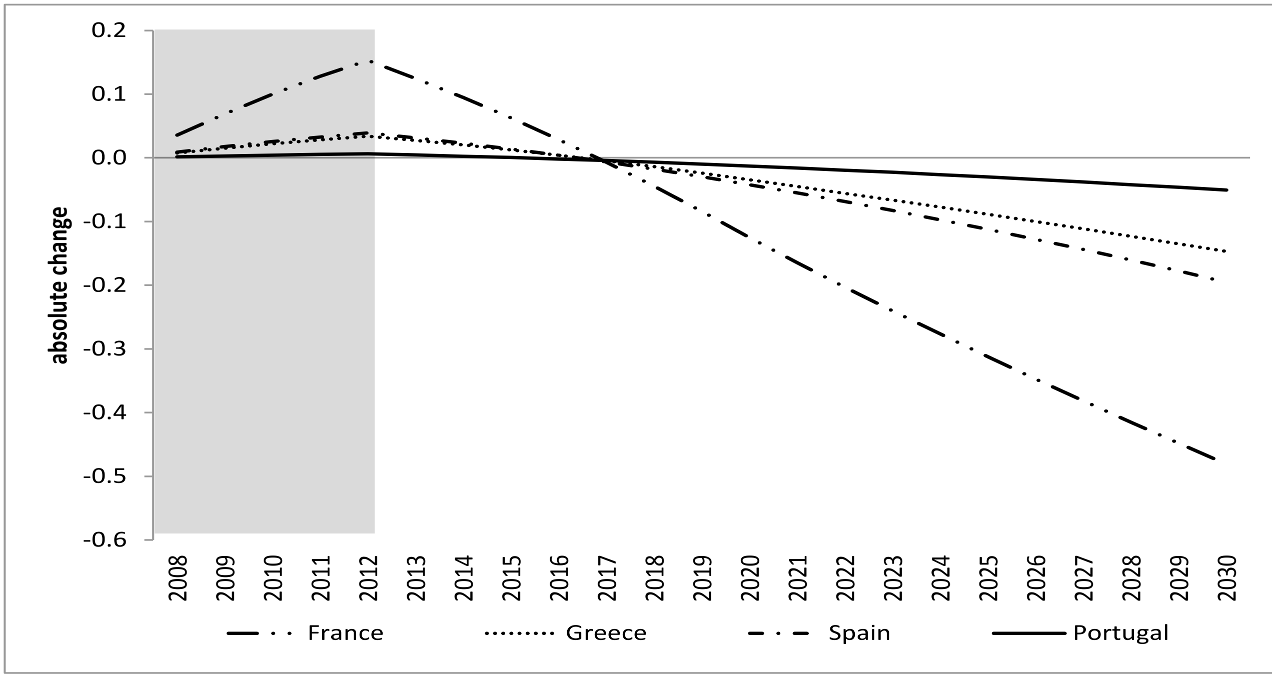
Table 4: Selected EU countries results in the No-Ad and Ad scenarios in 2030 wrt reference scenario

	No-Ad scenario						
	GDP (% change)	Regional savings	Import	Export	Investment	Deficit ($ billion change)	Debt ($ billion change)
France	-0.28	-39.91	0.49	-4.81	-2.31	57	639
Greece	-0.36	4.39	-0.14	-1.63	-2.24	2	19
Spain	-0.40	-7.14	-0.66	-1.50	-2.70	11	116
Portugal	-0.39	-6.97	-0.80	-0.41	-2.68	1	6
	Ad scenario						
	GDP (% change)	Regional savings	Import	Export	Investment	Deficit ($ billion change)	Debt ($ billion change)
France	-0.21	-26.51	0.20	-2.84	-1.55	43	558
Greece	-0.25	2.90	-0.13	-1.02	-1.48	1	17
Spain	-0.26	-4.88	-0.43	-1.01	-1.76	8	101
Portugal	-0.26	-5.18	-0.50	-0.35	-1.73	0	5

Source: ICES-XPS model

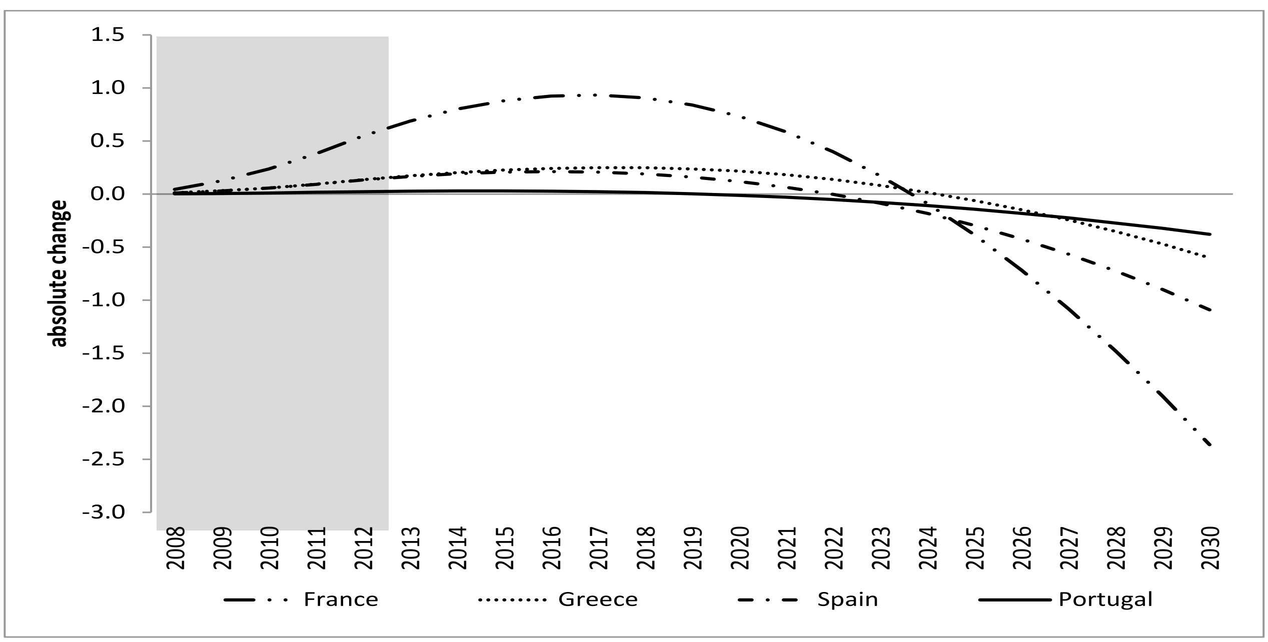
Table 4 confirms that in the medium term GDP decreases less in the Ad than in the No-Ad scenario with adaptation reducing the penalization on the investment path. Furthermore, both deficit and debt are lower. Figure 5 and 6 depict the change in the deficit/GDP and debt/GDP ratios which are again qualitatively similar to that of Italy.

Figure 5: deficit/GDP ratio in the Ad scenario wrt No-Ad scenario in other PIIGS countries



Source:ICES-XPS model

Figure 6: debt/GDP ratio in the Ad scenario wrt No-Ad scenario in other PIIGS countries



Source: ICES-XPS model

5. CONCLUSIONS

In this paper we explored the possibility for Italy and other highly indebted EU countries to increase public adaptation expenditure without raising new taxes and improve at the same time the sustainability of public budgets. We demonstrate that this might be feasible, using a recursive dynamic CGE model featuring a detailed description of the public sector and of its accounts. Specifically, we show that proactive adaptation against river floods, financed by government borrowing (i.e. in deficit spending), can in the medium term decrease GDP losses and feature a slower increase in public deficit and debt than a no adaptation scenario. Similarly, after an initial phase in which they are increasing, also the deficit/GDP and the debt/GDP ratios decline. In other words adaptation (in this particular case against flooding), by protecting the productive capacity of the economic systems, prevents further future expenditures by the government. Over a sufficiently, but not excessively, long time period, saved expenditure more than counterbalances initial higher adaptation expenditure, including higher interest payments, with positive effect on public finance sustainability.

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APPENDIX A: OVERVIEW OF THE ICES-XPS MODEL

The model uses a Walrasian perfect competition paradigm to simulate market adjustment processes. Industries are modeled through a representative price-taker firm that minimizes its production costs. Output prices are given by average production costs. The production functions are specified via a series of nested Constant Elasticity of Substitution (CES) functions. Domestic and foreign inputs are imperfect substitutes, according to the Armington assumption.

A private representative consumer in each region receives income ($\mathrm{YH_r}$), defined as the service value of national primary factors (natural resources, land, labour, capital). Capital and labour are perfectly mobile domestically, but immobile internationally. Land and natural resources, on the other hand, are industry-specific.

In mathematical terms, equation (1) describes private income respect to sources. It is composed of four main elements according to sources: (i) factor use remuneration (divided into labour and capital income, $\mathrm{YHL_r}, \mathrm{YHK_r}$ respectively); (ii) social transfers from the government ($\mathrm{YHTR_r}$); (iii) the net of other transfers between private households and government ($\mathrm{YHOGI_r}, \mathrm{YHOGE_r}$) which is functional to the balancing of the base year; (iv) income from interest on public debt ($\mathrm{YHI_r}$).

$$\mathrm{YH_r} = \mathrm{YHL_r} + \mathrm{YHK_r} + \mathrm{YHTR_r} - \mathrm{YHOGI_r} + \mathrm{YHOGE_r} + \mathrm{YHI_r} \tag{1}$$

Where:

$$\mathrm{YHTR_r} = \alpha_{\mathrm{TR,r}} \cdot \mathrm{YG_r} \tag{2}$$

$$\mathrm{YHOGI_r} = \alpha_{\mathrm{OGI,r}} \cdot \mathrm{YH_r} \tag{3}$$

$$\mathrm{YHOGE_r} = \alpha_{\mathrm{OGE,r}} \cdot \mathrm{YG_r} \tag{4}$$

$$\mathrm{YHI_r} = \mathrm{INTD_r} + \mathrm{INTI_r} \tag{5}$$

Transfers are fixed shares of the income of the agent paying out the transfer. For instance, social transfers from government to the private household (equation (2)) are a fixed share

($\alpha_{TR,r}$) of the government income. Similarly, other expenditures (equations (3)-(4)) are respectively fixed shares of government and household income (according to shares $\alpha_{OGE,r}$ and $\alpha_{OGI,r}$). Interest income to households (equation (5)) is the sum of interest paid from the domestic government and interest from abroad.

This income is used to finance aggregate household consumption ($PRIV\_EXP_r$) and household savings ($PRIV\_SAV_r$). The expenditure and saving shares are fixed ($\beta_{PEXP,r}$ and $(1-\beta_{PEXP,r})$, respectively), which means that the top-level utility function has a Cobb-Douglas specification. Formally, equation (6) defines the private income equation respect to uses; equations (7) and (8) isolate the Cobb-Douglas structure between consumption and savings.

$$YH_r = PRIV\_EXP_r + PRIV\_SAV_r \tag{6}$$

$$PRIV\_EXP_r = \beta_{PEXP,r} \cdot YH_r \tag{7}$$

$$PRIV\_SAV_r = (1-\beta_{PEXP,r}) \cdot YH_r \tag{8}$$

Then, private consumption is split in a series of alternative composite Armington aggregates. The functional specification used at this level is the Constant Difference in Elasticities (CDE) form: a non-homothetic function, which is used to account for possible differences in income elasticities for the various consumption goods. In mathematics, equation (9) represents the identity between regional private expenditure and its decomposition into prices and quantities, while equation (10) states that total regional private consumption is nothing else than the sum of private consumption by goods.

$$PRIV\_EXP_r = PPRIV_r \cdot QPRIV_r \tag{9}$$

$$PPRIV_r \cdot QPRIV_r = \sum_i PP_{i,r} \cdot QP_{i,r} \tag{10}$$

The government is a separate actor, and the model enriches the representation of public expenditures.

It receives income from four main sources: (i) tax revenues ($TTAX_r$); (ii) the net transfers with private households ($YHOGI_r - YHTR_r - YHOGE_r$); (iii) net interest payments to resident and non- resident households (YGI_r); (iv) net foreign transfers among governments ($AIDI_r - AIDO_r$)

Government income is used for consumption ($\mathrm{GOV\_EXP_r}$) and savings ($\mathrm{SAV\_GOV_r}$). Equations (11) and (12) represent the government income respect to sources and uses.

$$\mathrm{YG_r = TTAX_r - YHTR_r + YHOGI_r - YHOGE_r - YGI_r + AIDI_r - AIDO_r} \tag{11}$$

$$\mathrm{YG_r = GOV\_EXP_r + SAV\_GOV_r} \tag{12}$$

Where:

$$\mathrm{YGI_r = INTD_r + INTO_r} \tag{13}$$

$$\mathrm{AIDO_r} = \alpha_{\mathrm{AIDO,r}}\mathrm{YG_r} \cdot \mathrm{aidout_r} \tag{14}$$

$$\mathrm{AIDI_r} = \overline{\mathrm{AIDI_r}} \cdot \mathrm{aidin_r} \tag{15}$$

Equations (13)-(15) show the definition of the new variables. $\mathrm{YGI_r}$ is the total amount of interest paid from a government (so it is the sum of payment to residents ($\mathrm{INTD_r}$) and non-residents ($\mathrm{INTO_r}$)). Outflows of grants ($\mathrm{AIDO_r}$) are a fixed share of government income, multiplied by a scaling parameter ($\mathrm{aidout_r}$) which reflects the change in the global amount of grants to be allocated. Inflows of grants ($\mathrm{AIDI_r}$), are simply rescaled considering the initial level.

Since there is no bilateral matrix to track international transfers (i.e. grants), we use the approach described in McDonald and Sonmez (2004), where an artificial accounting agent (named “Globe”) collects all outflows and distribute them to the countries. This leads to a clearing condition (equation (16)) in the global market of aid of this kind:

$$\textstyle\sum_{\mathrm{r}} \overline{\mathrm{AIDI_r}} \cdot \mathrm{aidin_r} = \sum_{\mathrm{r}} \overline{\mathrm{AIDO_r}} \cdot \mathrm{aidout_r} \tag{16}$$

Government income is used to consume and save according to equation (12). Regional real government expenditures are a fixed share of real regional GDP (equation (18)), while nominal expenditures are the sum of the single commodity consumption (equation (19)).

$$\mathrm{GOV\_EXP_r = PGOV_r \cdot QGOV_r} \tag{17}$$

$$\mathrm{QGOV_r} = \beta_{\mathrm{GEXP,r}} \cdot \mathrm{QGDP_r} \tag{18}$$

$$\mathrm{PGOV_r} \cdot \mathrm{QGOV_{r_r}} = \sum_i \mathrm{PG_{i,r}} \cdot \mathrm{QG_{i,r}} \tag{19}$$

Total regional investments are modeled through a Cobb-Douglas function of private and public investments. Formally, regional investment net of depreciation $(\mathrm{NETINV_r})$ is split into public $(\mathrm{GOV\_INV_r})$ and private investments $(\mathrm{PRIV\_INV_r})$ according to fixed shares (equation (20)).

$$\mathrm{NETINV_r} = \mathrm{GOV\_INV_r} + \mathrm{PRIV\_INV_r} \tag{20}$$

Where:

$$\mathrm{GOV\_INV_r} = \varepsilon_r \cdot \mathrm{NETINV_r} + \Delta\mathrm{GOVINV_{CNST,r}} \tag{21}$$

$$\mathrm{PRIV\_INV_r} = (1 - \varepsilon_r) \cdot \mathrm{NETINV_r} \tag{22}$$

and $(\Delta\mathrm{GOVINV_{CNST,r}})$, are additional adaptation infrastructure investments.

The gap between public savings and public investments is the amount of borrowing the government requires. This gap is financed by private households. Both domestic and foreign households supply a homogenous saving commodity. Therefore, equation (23) is satisfied in each time period of the simulation:

$$\mathrm{I\_GOV_r} = \mathrm{SAV\_GOV_r} + \mathrm{GBOR_r} \tag{23}$$

Note that a positive value of the variable $\mathrm{GBOR_r}$ means a deficit, thus the government is borrowing, while a negative sign means a surplus so that the government is a lending resources.

Investment is internationally mobile: regional savings (private plus public) from all regions are pooled and subsequently investment is allocated to achieve equality of expected rates of return to capital in the long term. Savings and investments are equalized at the world, but not at the regional level. Therefore, each region could have an imbalance between disposable savings and investment demand, which is closed by a surplus/deficit in foreign transactions (considered as the sum of trade surpluses/deficits and the net inflows of international transfers). An important role is played by government borrowing since it reduces the availability of regional savings with a consequent increase in saving prices which are negatively correlated to the rate of return to capital. Therefore, a country can attract more investment and increase the rate of growth of its capital stock when its GDP and its rate of return to capital are relatively higher than those of the other countries, or its government necessitates a lower level of borrowing.

The ICES-XPS model is a recursive dynamic model, thus each year is linked to the previous one via capital accumulation. The structure of the debt accumulation for the government is close to the capital accumulation. There is a stock from the previous simulation year $(\mathrm{GDEBT}_{t-1,r})$ which is increased by government's borrowing in the current simulation year $(\mathrm{GBOR}_{t,r})$. Denoting the current simulation year as t and the previous year as t-1, we have the following accumulation rule:

$$\mathrm{GDEBT}_{t,r} = \mathrm{GDEBT}_{t-1,r} + \mathrm{GBOR}_{t,r} \tag{24}$$

Then, we split the accumulation rule to consider the repayment of debt for domestic and foreign households according to a fixed share fdshr_r, defined as the share of foreign debt on total debt in region r in the base year. So equation (24) becomes:

$$\mathrm{GDDEBT}_{t,r} = \mathrm{GDDEBT}_{t-1,r} + (1 - \mathrm{fdshr}_r) \cdot \mathrm{GBOR}_{t,r} \tag{25}$$

$$\mathrm{GFDEBT}_{t,r} = \mathrm{GFDEBT}_{t-1,r} + \mathrm{fdshr}_r \cdot \mathrm{GBOR}_{t,r} \tag{26}$$

Interest payments on government's domestic and foreign debt stocks $(\mathrm{INTD}_{t,r}, \mathrm{INTF}_{t,r})$ are defined as an exogenous interest rate (ir_r) multiplied by the related previous year debt stock (equations (27)- (28)). This means that interest payments are a consequence of the level of indebtedness (Lemelin and Decaluwé, 2007)

$$\mathrm{INTD}_{t,r} = \mathrm{ir}_r \cdot \mathrm{GDDEBT}_{t-1,r} \tag{27}$$

$$\mathrm{INTF}_{t,r} = \mathrm{ir}_r \cdot \mathrm{GFDEBT}_{t-1,r} \tag{28}$$

Similarly to the case of international grants, there is a clearing condition (equation (29)) also in the world market for interest payments. This condition ensures that the total amount of interests governments pay to non- residents equals the total amount of interest payments from abroad. This does not mean that there is a balance in outflows and inflows of foreign interest payments but each country could face a positive or negative net value.

$$\sum_r \mathrm{INTI}_{r,t} = \sum_r \mathrm{INTF}_{r,t} \tag{29}$$

Moreover, each country receives an amount of interests from abroad that depends on the mean value of the interest collected in the world market (from equation 30), and on a scaling parameter ($\mathrm{psavshr}_{r,t-1}$) which represents the country contribution to world private investment in the previous year.

$$\mathrm{psavshr}_{r,t-1} = \frac{\mathrm{SAV\_PRIV}_{r,t-1}}{\sum_r \mathrm{SAV\_PRIV}_{r,t-1}} \tag{30}$$

This share reflects by how much private households in each country contribute to finance total world debt. Since public and private savings are homogenous goods, private households lend a fraction of their savings to governments. As a consequence, the public agent pays interests to the household. If households save more, they could devote a higher fraction of their savings to finance public debt. This means that at time t+1 they obtain higher interest payments. Therefore, foreign interest inflows become:

$$\mathrm{INTI}_{r,t} = \mathrm{INTAVI}_r \cdot \mathrm{psavshr}_{r,t-1} \tag{31}$$

1) *Government closure rule choice for ICES-XPS model*

When the public agent is introduced in a Computable General Equilibrium model, the modeler has to choose how to close the sector, in other words, he has to decide the causality among income, expenditures and savings (Robinson, 2003). There are essentially two alternatives: (i) endogenous government savings and the other components exogenous, or (ii) the other way round with exogenous government savings. Since, in this deliverable we want to use the ICES-XPS model to assess the budgetary effects of impacts and adaptation expenditures we follow the first approach. Therefore, taxes have exogenous tax rate, expenditures (both recurrent and investments) are fixed exogenously and as a consequence the model calculates the final savings (or public borrowing) as the gap between revenues and expenditures. However, there are no projections for government expenditures up to 2050. Some estimates are in IMF's World Economic Outlook (IMF, 2016) up to 2020 but there is no clear and unique correspondence between its aggregate "general government total expenditures" and the ICES-XPS variables. Therefore, to project these variables in the baseline we apply two different approaches: (i) real recurrent expenditures are a fixed share of real GDP (Chateau et al. 2014); (ii) real government investments are a fixed share of total regional investments, so that public and private investments are a Cobb-Douglas function respect to total (depreciated) regional investments.

Considering fixed government expenditures is as to assume that the government has a sort of "minimum" level of expenditures it wants to maintain even in other scenarios, when, for instance, impacts or adaptation occur. Moreover, this choice allow us to have a more clear link between inputs and the final outcomes.