CER-ETH – Center of Economic Research at ETH Zurich

Getting the Costs of Environmental Protection Right

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Working Paper 20/341
August 2020

Economics Working Paper Series

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Getting the Costs of Environmental Protection Right

Why Climate Policy is Inexpensive in the End

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August 5, 2020

Abstract

The belief that stringent climate policies are very costly is widespread among political decision-makers and the public. The Trump administration stressed the cost argument as the motivation for the US withdrawal from the Paris Climate Agreement. However, such judgements ignore the economic benefits of policy changes and implicitly build on a misguided decomposition of environmental impacts using the $IPAT$ and $Kaya$ identities. The paper shows that this method predicts policy-induced income losses that are systematically and significantly biased. I extend the decomposition analysis by introducing input substitution, which leads to the $IPAST$ identity. By additionally incorporating a production approach, causal relationships between drivers of resource use, and a Romer-Kremer framework for technology development in a Schumpeterian tradition, I develop the IAT rule, a structural equation to easily estimate climate policy effects. For a given decarbonization path, I use the different rules to calculate the projected income development at the global and country level. The use of the IAT approach instead of agnostic decomposition suggests that the costs of a stringent climate policy are much lower than normally expected, which supports deep decarbonization.

Keywords: Environmental protection; costs of climate policy; decarbonization; *IPAT* identity; *IAT* formula.

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1 Introduction

The need for stringent climate policies is widely accepted but this equally holds for a persistent public belief: that policies are very costly. It is obvious that firms, sectors, and regions earning their income by supplying fossil fuels or by producing fossil-intensive goods experience significant costs with decarbonization (McGlade and Ekins 2015). However, renewable energies and new technologies pave the ground for new business opportunities and clean development initiatives which are a benefit for other sectors of the economy (Barbier 2012). An aggregate economic assessment of climate policies in a holistic economic-ecological system has to include many different effects which greatly complicates the analysis. This may be the reason why simple formulas that appear to give at least a rough estimate of the effects have been warmly embraced. Prominently, the $IPAT$ and the $Kaya$ identities decompose environmental impact of an economy in multiplicative components encompassing population, income, technology, and pollution intensity, see Ehrlich and Holdren (1971) and Kaya and Yokoburi (1997). Despite the deep concern that identities and statistical decompositions do not imply any causalities (Alcott 2010), the approach has been prominently called a "useful way to start thinking about what drives the sizes of the economy's impacts on the environment" (Perman et al. (2011). It has been widely used as an introduction to economics of the environment and plays a core role in the works of the IPCC, which is a good reason in itself to reconsider the procedure prominently. The Special IPCC Report on Emissions Scenarios (Nakicenovic et al. 2000) applies a range of assumed conditions for past and future development of the different $Kaya$ components. The IPCC WG3 concludes in the Fifth Assessment Report that there is high "evidence" and high "confidence" that "per capita production and consumption growth is a major driver for worldwide increasing GHG emissions" and that "population growth aggravates worldwide growth of GHG emissions" and conclude that "the improvements in energy intensity of GDP that the world has achieved over the last four decades could not keep up with the continuous growth of global population resulting in a closely synchronous behavior between GDP per capita and CO2 emission during the period" (Blanco et al. 2014). By adding that reductions in energy and carbon intensities have been "insufficient" so far to offset the effects of income and energy growth on overall emissions the report directly follows the logic of the $Kaya$ decomposition, focusing on population, income, and technology as "drivers" of GHG emissions.

The $IPAT$ and $Kaya$ formulas are simple identities which can never be wrong in mathematical terms. So how can they be wrong when applied to the real world? The problem occurs when implicitly deriving causal relationships from them, which has drastic consequences for the assessment of climate policies. It mainly says that, with given technology, carbon emissions are proportional to income and population so that a decarbonization is closely linked to these "drivers." Even when assuming a realistic rate of "technical progress," requiring substantial carbon reduction would suggest that degrowth of income is needed to combat climate change, which may be welcomed by some but is clearly unattractive for the broad public, especially in the less developed countries. The paper argues that fundamental economic insights and empirical regularities are violated when drawing such conclusions. I show below that adding one straightforward component to the $IPAT$ identity radically alters the policy results. To address the issue of missing causalities I then include a link between technology and population which delivers a more accurate but still simple rule which is the IAT formula. To avoid a switch in methodology the IAT model is kept as close to $IPAT$ as possible; it appears not sufficient to present a complex integrated assessment model as an alternative to the simple identities. Even when giving a highly simplified picture of reality these rules need to meet three requirements to qualify as useful theory. First, to be empirically meaningful a rule needs to capture the most important mechanisms at work. Second, the rule has to quantify the important effects in a way which is not systematically biased. Third, the different effects covered by a rule should be mutually consistent i.e. not contradict each other when applied to the real world. The paper shows that the $IPAT$ identity fails in all three respects. Still it is prominently used because it is simple and seen as innocuous being just an identity. The paper proposes IAT as a preferable alternative.

The paper builds on the works of three recipients of the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 2018 and 2019: William Nordhaus, Paul Romer, and Michael Kremer. The 2018 laureates were honored for designing the tools that are necessary to examine how humanity copes with limited resources and the constraints on resource use which reflect nature and knowledge, the topic of this contribution. The substitution effect and the production approach introduced below have their analogues in the DICE model of William Nordhaus[2] where a production function and emission abatement activities are employed. The population equation used below refers to the model of the innovation sector developed by Paul Romer[3] in the tradition of Joseph Schumpeter,[4] where higher population is interpreted as allowing for more potential inventors. In 2019, Michael Kremer was awarded the price for co-developing an experimental approach to alleviating global poverty, while the present paper refers to one of his earlier contributions on population growth and innovation.[5] Like Paul Romer he argues that total research output grows with population due to the nonrivalry of technology and presents empirical evidence confirming the hypothesis. By adopting a Romer-type innovation sector to explain economic growth and linking it to resource and the climate, analyzed by Nordhaus, the present paper connects the contributions of these three authors.

2 IPAT revisited

The $IPAT$ identity decomposes environmental impact (I) into three factors labeled population (P), "affluence" (A), and "technology" (T) by expanding impact I with population P and income (Y) so that $I = P \cdot (Y/P) \cdot (I/Y)$. "Affluence" is defined as per capita income, Y/P, and impact intensity, I/Y, is said to represent "technology (T)." To move

[2] Nordhaus (2017)
[3] Romer (1990)
[4] Schumpeter (1912)
[5] Kremer (1993)

the approach closer to economics and the climate problem I define impact I as the use of polluting natural resources (fossil fuels) R and relabel population P by L to highlight the role of population as workforce (L = labor). Improving technology reduces input intensity, R/Y, and raises resource productivity, Y/R; I will use both interpretations below. The decomposition then reads

$$R = L \cdot Y/L \cdot R/Y. \tag{1}$$

$$\mathbf{I} \;=\; \mathbf{P} \quad \mathbf{A} \quad \mathbf{T}$$

The $Kaya$ identity additionally considers emission intensity of resources and expands resource use by carbon emissions V such that $V = L \cdot (Y/L) \cdot (R/Y) \cdot (V/R)$. Like the $IPAT$ identity $Kaya$ does not present any causalities; it is a tautology because canceling out terms simply yields $V = V$, i.e. "carbon = carbon." In both cases it appears innocuous to take growth rates (denoted by hats) which yields for the $IPAT$ identity

$$\hat{R} = \hat{L} + \widehat{Y/L} + \widehat{R/Y}. \tag{2}$$

Expression 2 says that the growth rate of resource use is given by the sum of the growth rates of population, per capita income, and resource intensity. This is of course correct as well but still the equation does not involve any causalities. What is thus incorrect is to call the variables on the right hand side the "drivers" of resource growth, mainly for two reasons. First, there is no external validity for the assumption that a sufficient number of factors has been identified on the right hand side of the equation. Adding more variables may change the interpretation considerably. Second, the interpretation of the right-hand variables as independent "drivers" suggests that we can vary one of them at the time while leaving the other factors unchanged, which is not generally possible. Rather, in reality the variables are closely interlinked which can be shown using relevant theory which I will do below. The same assessment applies for emission growth in the Kaya identity. As using fuels with less carbon content is not relevant for the paper results I concentrate on the $IPAT$ identity in the following.

The $IPAT$ approach suggests that, in order to obtain a significantly negative $\hat{R}$ that is requested by decarbonization, we need fast technical progress (highly negative $\widehat{R/Y}$) to overcompensate positive population growth ($\hat{L}$) and income growth ($\widehat{Y/L}$). When the improvements of technology are not sufficiently strong it concludes that the task of a stringent climate policy rests on population and income development. In the quantitative section below I show that, using realistic numbers, the $IPAT$ equation says that decarbonization is coupled to a degrowth of income: a very strong but highly controversial result. To show the main misconceptions of the simple decomposition approach, I next analyze the link between resources and output, then introduce a separate term for input substitution, reconsider technical progress, and finally explain the role of population growth.

3 Resources and output

To focus on the relationship between resource use and income I rearrange $IPAT$ to have Y on the left hand side of the equation and disregard L on the right hand side for a moment so that

$$Y = \frac{Y \cdot L}{R \cdot L} R = \frac{Y}{R} \cdot R = \tilde{T} \cdot R. \quad (3)$$

where the ratio $\tilde{T} = Y/R$ is now labeled "technology"; it is simply the inverse of the corresponding term T in $IPAT$. Using Eq. (3) as a structural relationship suggests that a decrease of resource use R causes a proportional decrease of income Y, assuming $\tilde{T}$ constant. Strict proportionality between the two variables means that income has to decrease significantly to lower resource use when technical progress is absent. This is illustrated in Figure 1 which displays a Y-R diagram; $\tilde{T}$ is depicted as the slope of the straight line through the origin. To reduce resources in the quantity $R_2 - R_1$ income has to shrink in the amount of $Y_2 - Y_1$ which shifts the economy from point B to A. Hence, when applying $Y = \tilde{T} \cdot R$ in the sense of a causality, the burden of reducing resource use by x percent consists of shrinking income by the same x percent, which evidently entails a huge cost.

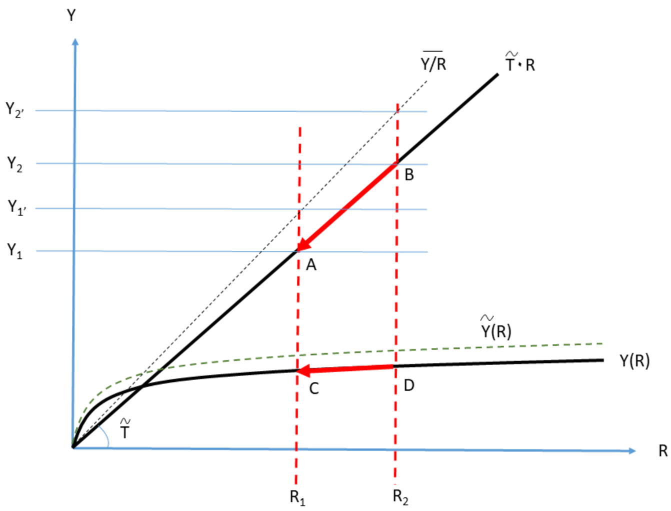

Figure 1: Resource-output relationship

The flaw of this "conventional" reasoning is the posited constancy of the slope $\tilde{T} = Y/R$ which has no empirical content. R is an input in production and Y, the income level, is closely related to economic output; for simplicity I will not distinguish between the two variables and use Y for both. Applied to real production processes, a linear relationship would imply that a twenty percent increase in resource input, say fossil fuels, could raise output in the economy by twenty percent. There is ample empirical evidence that this does not hold because returns to resource input are decreasing; for resources the law of diminishing returns is firmly established, see e.g. Perman et al (2011). Moreover, the average share of natural resources in total production cost is a few percent only, so that the effect of diminishing returns for this input kicks in early, which results in a strongly bent function $Y(R)$ in the figure; the function explicitly expresses the causality from resource R to output Y. Hence, a twenty percent increase in the use of resources would raise output by a much lower percentage; the other inputs like labor and capital are held constant in this exercise (like in well-known "growth accounting"). Importantly, the function $Y(R)$ in the figure suggests that a decrease in resource quantity $R_2 - R_1$ has only a minor impact on income. This insight will play a major role in the final conclusions.

The ratio R/Y included in $IPAT$ is a relationship between one input and total output i.e. resource intensity reflecting many characteristics of the economy and not just "technical progress." We easily see that the $IPAT$-identity $R = Y \cdot \frac{R}{Y}$ is still valid when using $Y(R)$ instead of Y/R. But realistically applying $Y(R)$ the effect of environmental policy (reduction of R) is a significant decrease in the resource intensity R/Y while output Y decreases only to a minor extent. In a real economy, the adjustment to emission reduction policy does not primarily happen via shrinking output but through changes in input composition. The reduction of one input, R, holding the other inputs constant, raises factor productivity Y/R significantly, because resources become relatively scarce.

4 IPAST identity

Based on an empirically meaningful resource-output link I now add input substitution as a "driver" of resource use through extending the $IPAT$ identity by an additional term X representing production inputs other than resources; X can be thought of as being broad (real) capital, including machines and buildings but also infrastructure needed for renewable energies such as dams and windmills. To represent input intensities subject to substitution, the ratio R/X is considered and labeled by "S" (substitution). "Technology" is measured by the productivity of machines etc. where in reality technical innovations are applied, i.e. it is given by the ratio of input X to output Y; technology is thus expressed in terms of input intensity like in $IPAT$. The new "$IPAST$" decomposition reads

$$R = L \cdot Y/L \cdot R/X \cdot X/Y. \tag{4}$$

I = P A S T

As in the case of $IPAT$ this unambiguously holds at all times because it is an identity i.e. a simple expansion of resource use R. It has its roots in exactly the same decomposition logic as used with $IPAT$ and should thus deserve the same level of appreciation. Including the new element in the extended $Kaya$ identity we get $V = L \cdot (Y/L) \cdot (R/X) \cdot (X/Y) \cdot (V/R)$. Taking growth rates of the $IPAST$ formula yields

$$\hat{R} = \hat{L} + \widehat{Y/L} + \widehat{R/X} + \widehat{X/Y}. \tag{5}$$

Like with the $IPAT$ identity, population growth, income growth per capita, and "technical progress" (reduction of X/Y) have a direct effect on resource use while the term $\widehat{R/X}$ has now been added. The new term highlights that a main, previously omitted "driver" of resource use is the intensity of resources relative to other inputs in production and consumption. Note that it is distinct from the emission intensity used in the $Kaya$ equation which only covers substitution among different fossil fuels, a minor part of the whole substitution process. Importantly, the $IPAST$ approach suggests that, in order to reduce resource use ($\hat{R} < 0$), it is feasible to use less resources relative to other inputs ($\widehat{R/X} < 0$) while population (L), per capita income (Y/L), and technology (X/Y) remain constant! Hence, a simple and correct extension of the original $IPAT$ setup completely changes the policy conclusions: It suggests we can achieve a reduction in resource use *without* reducing income or population growth, which sheds a much brighter light on the economic effects of climate policy. Notably, it shows the broad range of possible conclusions reached by agnostic decomposition analysis. When using $IPAST$ instead of $IPAT$ the focus of climate policy shifts to decarbonization in production and consumption, that is to reducing the polluting input via factor substitution and use of alternative means for heating, transportation, and industrial processes. To conclude, adding a new driver - substitution - alters the debate about the drivers of resource use and climate change drastically. The requirement of completeness for a useful rule is obviously violated by the $IPAT$ identity.

Some qualifications are warranted at this point. First, neither $IPAT$ nor $IPAST$ are based on a theoretical framework including causal relationships. Hence, their degree of "realism" or "usefulness" does not differ, yet the conclusions differ fundamentally. Second, while $IPAT$ is very pessimistic about the costs of climate policy, $IPAST$ can be seen as too optimistic, because in reality the substitution of natural resource by other inputs has some costs. But the cost argument equally holds when resource reduction is achieved by other means e.g. via subsidies for innovation or population policy. Third, both identities have to be checked with respect to the other requirements for "basic rules." These will be discussed when focusing on technical progress and population which is done in the next section before I aim to take a more holistic approach with the IAT formula.

5 Progress and population

The usual interpretation of the $IPAT$ identity suggests that technical progress is expressed as input productivity growth raising the ratio $\tilde{T} = Y/R$. According to the decomposition argument, progress would allow Y to rise with unchanged R or, alternatively, to reduce R with constant Y. This seems intuitive but has an implication contradicting empirical observations. If we multiply Y/R by a positive factor, say $a > 1$, we get a steeper straight line in Figure 1, e.g. given by the dotted ratio $\overline{Y/R}$. It means that, using the better technology, a given reduction in resource quantity, say $R_2 - R_1$, has a higher negative impact on income, as $Y_{2'} - Y_{1'} > Y_2 - Y_1$, which is not in line with what we would expect, which is that technical progress improves the conditions for resource savings. In the production approach presented as an alternative above, improving technology shifts the $Y(R)$ curve upward, say to $\widetilde{Y(R)}$ represented by the dotted line. Given the curvature of the input-output relationship, technical progress shifts the $Y(R)$ curve upward, what one would expect, and affects its slope in the $Y - R$ space, but to a much lesser degree. To conclude, the labeling and the role of technical progress in $IPAT$ is not convincing. Moreover, the issues of endogeneity of income and population as well as the causal relationships between the "driving" factors need to be addressed, to which I turn now.

In the traditional $IPAT$ reasoning, population is viewed as a main "driver" of natural resource use. It says that a growing population raises resource use proportionally which, looking at the absolute numbers for world population, is of course a big factor. Originally, the Malthusian causality went in the opposite direction: it stated that population size was determined by resource availability, which mainly meant limited food supply. Ironically, this constraint stopped to be effective in the time period when Thomas Malthus published his proposition in 1798. Nevertheless, Malthus and the focus on population size have remained very popular since then. That more people cause more pollution is an equation everybody is intuitively buying and, of course, it cannot easily be dismissed. But an accurate assessment of population size needs additional qualifications. First, there is a huge heterogeneity in resource use between people in the different countries, the gap in per capita emissions between the top and bottom countries exceeds a factor of 50 (Blanco et al. 2014). Second, population growth occurs in world regions where resource use is way below world average; increasing longevity in rich countries is becoming equally or even more important for resource use. Therefore, the request of lower population growth in less developed countries to curb carbon emissions is neither efficient nor equitable; with enforced and sex selective abortions it has created huge problems which have not been broadly admitted, see Ebenstein (2010) and Hesketh (2009). Third, many resource supplies like oil and gas are ultimately bounded so that resource demand cannot simply follow population increase one to one (Hotelling 1931). Fourth, what $IPAT$ captures is a *demand* effect, expressing that more consumers demand more resources; what it completely ignores are the *supply* effects of labor and resource inputs on production. In the following I refer to Paul Romer (Romer 1990) and Michael Kremer (Kremer 1993) who assume in the Schumpeterian tradition that the frontier of the world economy is pushed by innovation and that labor is the central input in the innovation process. In fact, it is skilled labor which is used in the labs but having more labor in general allows to educate more people, to allocate more people and time to develop new ideas, and to multiply the learning effects in research with the increasing scale; also it raises the probability that successful Schumpeterian innovators, bringing the novel ideas to the market, enter the stage. To keep the focus, the model does not distinguish between different regions, which is done by William Brock and Anastasios Xepapadeas.[6] The causal links between population, innovation, and resource efficiency are now included in a structural model resulting in the IAT equation.

6 IAT formula

To derive a simple theory-based rule for the effects of decarbonization I start from a standard aggregate production function where output depends on technical knowledge $\tilde{T}$ and the inputs labor L, capital K, and resources R. Specifically, I use the production function $Y_t = B\tilde{T}_t^{\kappa} L_{Y,t}^{\alpha} K_t^{\beta} R_{Y,t}^{1-\alpha-\beta}$ where $B > 0$ is a constant, t is the time index, and L_Y and R_Y denote labor and resources used for goods production (parts of labor and resources are also used in research, see below); the Appendix shows how the aggregate function is derived from production on firm level. With this widely used multiplicative function for production,

[6] Brock and Xepapadeas (2017)

each input can substitute for the other inputs i.e. the substitution effect of the $IPAST$ identity is accommodated and will not appear separately below. Moreover, each input is "essential," that is output is nil if only one of them is absent, which addresses the concern that we may become too optimistic with respect to substitution. For the parameters in the production function (output elasticities) I assume $0 < \alpha, \beta, \kappa < 1$ i.e. decreasing marginal returns for each input. Growth of each input has a positive impact on output growth, which is weighted by the output elasticity of the input. Technical knowledge is a non-rival input into production i.e. it can be used by all the agents at the same time. For labor, capital, and resources the elasticities are α, β, and $1 - \alpha - \beta$; they add up to unity which is what Paul Romer (1990) called the "standard replication argument" saying that returns to scale for rival inputs jointly should be constant. I further assume that new technologies raising $\tilde{T}$ do not fall like "manna from heaven" but are the result of purposeful investments in research. Following Paul Romer (1990) and Michael Kremer (1993) I consider a research sector where labor is the main input and labor productivity grows with existing knowledge due to positive knowledge spillovers. It has been forcefully argued that resources should also be considered as an essential input in the research sector, which at the same time helps to avoid the scale effect of growth.[7] Then, part of labor and of resources are used for research and the additional technical knowledge in time increment dt can be written as $d\tilde{T}/dt = L_{T,t}^{\gamma} R_{T,t}^{1-\gamma} \tilde{T}_t$ which features input substitution like for final goods; the T-subscripts denote inputs used in research and $0 < \gamma < 1$ is the output elasticity of labor in the research sector, growth of technology is given by $\frac{d\tilde{T}/dt}{\tilde{T}} = g$. With lower resource use, innovation growth can be kept on a constant level provided that more labor is allocated to research activities. As labor input is central for creating innovations, which help to save on resources, its role in the overall assessment of resource use changes substantially. In the Appendix I show how the supply and demand effects of labor can be included by combining final output and research to calculate the IAT formula which reads

$$R = C \cdot (\frac{Y}{L})^{\Phi} \cdot \tilde{T}^{\Psi} \tag{6}$$

I = A T

where $C > 0$ is a constant and the parameters in the exponents are derived from the model according to $\Phi = \frac{\gamma(1-\beta)}{1-\alpha-\beta}$ and $\Psi = -\frac{\kappa\gamma}{1-\alpha-\beta}$. Taking growth rates of the IAT equation yields

$$\hat{R} = \Phi \cdot \widehat{Y/L} + \Psi \cdot g \tag{7}$$

Like in $IPAT$, growth of "affluence" ($\widehat{Y/L}$) is positively linked to resource growth ($\Phi > 0$) while the effect of innovation growth (g) has a negative sign ($\Psi < 0$) as better technical solutions (higher $\tilde{T}$) allow for lower resource use. Population growth is not ignored but included indirectly in the IAT equation; it is a "driver" of the elements of the equation I, A, and $\tilde{T}$ i.e. it has an effect not only on resource use but also on per capita income growth and technology development in a Schumpeterian manner. Deriving the formula from

[7] A point highlighted by Groth and Schou (2002)

first principles shows that labor simply cannot be isolated as a "driver" of resource use, which would be needed for a useful simple formula. While the result of an income reduction with climate policy is similar to the $IPAT$ identity, the most important difference is that now the "drivers" of resource use have no longer a *proportional* impact on resources but a *nonlinear* effect; the coefficients Φ and Ψ in Eq. (6) are clearly distinct from unity. This is crucial for the economic assessment of climate policy. The effects depend on the size of the output elasticities which are calibrated in the next section.

IAT is a formula which explicitly includes central causalities between the different "drivers" of resource use. By displaying resource growth on the left hand side of the IAT equation, the presentation is similar to the $IPAT$ identity but, in a real production context, causality actually runs from inputs to output. Innovation growth (g) can be explicitly calculated using the Romer approach; see the Appendix.

7 Quantitative effects

In this section I use standard values from empirical studies for the used production parameters to calibrate the IAT equation and to compare the outcome with the $IPAT$ and $IPAST$ identities. The parameter values are as follows:

- output elasticity for resources in goods production (= cost share): $1 - \alpha - \beta = 0.04$,
- sum of output elasticities for labor and resources (= sum of cost shares): $1 - \beta = 0.8$,
- output elasticity for labor in research (= cost share): $\gamma = 0.98$,
- gains from diversification (innovation multiplier): $\kappa = 0.8$.

With this I obtain for the IAT equation that $\Phi = \Psi = 19.6$ which I round to integers for simplicity to have $\Phi = \Psi = 20$ i.e.

$$\hat{R}_t = 20 \left(\widehat{Y/L} - g \right). \tag{8}$$

The expression (8) says that, with given innovation growth ($g = const$), a reduction of the growth rate of resource use of one percentage point is associated with a reduction in the income per capita growth rate of 1/20 percentage point. This means that the mean of the predicted "costs" of climate policies are twenty times lower with IAT compared to $IPAT$. Note that causality runs from resource reduction to income growth, i.e. climate policy limits resource use for achieving the temperature targets thereby causing a minor delay in income development. The idea breeded by $IPAT$ that policy has to limit growth in order to limit resource use has no foundation in theory, it may even be counterproductive because policies slowing down growth would also slow down resource-saving innovation.

To illustrate the differences between the three main rules I am imposing the requirement of fast decarbonization for all the approaches. I specify a carbon trajectory on which resource use is reduced by five percent each year ($\hat{R} = -0.05$), which represents a path with more than 50 percent emissions reduction within 15 years. Applying the IPAT identity in the form $\widehat{Y/L} = \hat{R} - \hat{L} - \widehat{R/Y}$, taking the current growth rate of world population $\hat{L}$ of 0.01, and assuming annual technology growth $\widehat{R/Y} = \hat{T}$ of -0.03 the equation yields $\widehat{Y/L} = -0.03$ which says that annual per capita income growth rate has to be -3%. Stringent climate policy would thus strictly require a negative per capita income growth rate of minus three percent: what a gigantic cost of the policy! According to the calibrated IAT equation I write $\widehat{Y/L} = \hat{R}_t/20 + g$ where I posit technology growth $g = 0.03$ so that with $\hat{R} = -0.05$ I obtain $\widehat{Y/L} = 0.0275$. This means that fast decarbonization allows for annual output growth rate of 2.75% which is positive and still allows to rapidly increase living standards. It is less optimistic than the $IPAST$ identity which suggests the growth rate is not affected by climate policy because it assumes costless substitution of fossil fuels.

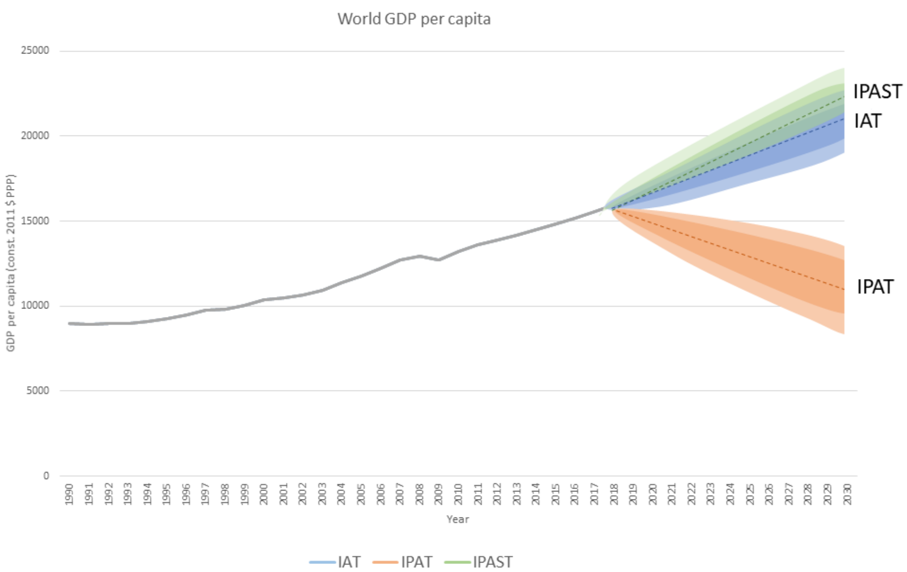

Figure 2: GDP per capita in the three scenarios

Figure 2 shows the global development of per capita income for 1990-2017 using the statistical numbers and for 2018-2030 depicting the predictions for the mean as well as the likely and the very likely ranges calculated with the different approaches. It becomes evident from the figure that IAT predicts a certain economic cost of climate policy as income development is slower than under $IPAST$ and that $IPAT$ predicts strong degrowth of income as a consequence of decarbonization.

Figures 3 in the Appendix shows GDP per capita in 2017 in a worldwide comparison of the different countries, while Figures 4-6 (see Appendix) depict the predicted income level in 2030 for the different approaches, provided that all countries share the global GDP per capita growth rate and that stringent climate policy ($\hat{R} = -0.05$) is equally enforced in all jurisdictions. It can be seen that the income positions of countries under $IPAST$ and IAT are very similar while under $IPAT$ it is predicted that with climate policy countries fall back in income which applies to all income levels but would be especially harmful for less developed countries. As a development perspective this would be highly unattractive and very likely to weaken the support for international climate policies.

8 Discussion and conclusions

A holistic climate economic model should accurately predict the effects of decarbonization on income, growth, innovation, and population size and establish the important links between these variables. The $IPAT$ identity is far from this standard: it presents a decomposition of different impacts which are all exogenously given and unrelated to each other. The $IPAST$ identity adds an important dimension to the simple decomposition setup and can mainly serve as a didactic piece, paving the way to a more comprehensive picture of the impacts. Highlighting the substitution effect supports decarbonization policy because it reduces the burden on the other "drivers." Of course, it needs to be put in a realistic perspective which is done in the last part of the paper, where the IAT rule employs basic insights from production and innovation theory. It adds the supply effects of labor and includes the causal relationships between the different drivers of resource use. The production setup is complemented by theory on innovation and economic dynamics, highlighting a Schumpeterian perspective on modern economies. On this fundament, the effects of climate policy can be assessed on an aggregate level, including important mechanisms and avoiding major biases. It emerges that degrowth of income is not needed to achieve the climate targets as suggested by the $IPAT$ reasoning. If degrowth of income should be desirable for other reasons, e.g. to "raise" general happiness, markets and policy may induce a reduction of investment activities. The positive growth rate achieved by the IAT equation results from optimal investment plans of the current generations, given a standard calibration of the parameters. The current world growth rate has been taken as a benchmark for the calculations; if world society wishes to have a lower growth rate in the future this can be achieved by market decisions and by policy, independent of decarbonization.

The quantitative part of the present paper is based on a decarbonization pattern which is consistent with the internationally agreed temperature targets, without discussing the probability that the necessary policies are implemented. One might argue that a larger world population is less likely to agree on stringent climate policies but there is no empirical evidence supporting the claim. It is not generally true that countries with high population growth have low climate policy ambitions; rather it appears that countries with high resource abundance are more likely to fear the cost of climate policies, the topic of this contribution. The results show that the costs of stringent climate policies become substantially lower when calculating them with IAT rather than $IPAT$. This should be useful information for applied scientists and decision makers having concerns about the political feasibility of decarbonization. The IAT rule cannot replace deep and extensive modelling of all the complex economic and ecological relationships but should help to build intuition on a realistic yet simple foundation. The rule is in no way a substitute for proper policy analysis but rather a supporting device for the design of efficient climate policy as discussed by Christian Gollier and Jean Tirole (Gollier and Tirole 2015). The factor 20 relating resource growth to output growth can serve as a rule of thumb when checking the policy impact without using a deeper model. The analysis covers the costs of climate policy but does not include its benefits, which depend on many complex issues such as avoided climate damages. To derive optimal temperatures and associated decarbonization from a cost benefit analysis we need highly sophisticated theoretical and Integrated Assessment Models, the simple rules will not do. It is a difficult task because it has to rely on appropriate climate damage functions, discount rates, and risk assessment.[8] International climate treaties implicitly assume that climate damages become very large when warming exceeds the agreed temperature targets, which is a valid proposition and adopted as a baseline assumption in the present analysis.

Policymakers should acknowledge that costs of climate policies are often misjudged while the benefits are generally well recognized. The paper shows why the widely used method of decomposing environmental impact calculates costs of climate policy that are far too high. The contribution develops an alternative formula that is still simple, but theoretically and empirically sound. The novel approach concludes that economic growth is only moderately reduced by a strict climate policy. Growth is still clearly positive, which is different from the degrowth message of decomposition analysis. The paper aims to bridge the gap between natural and social scientists at a central interface between the economy and the ecosystem. It seeks to coordinate views in the interdisciplinary dialogue on sustainable development and to provide a clear message to policymakers about the real economic costs of climate policy.

References

[1] Alcott, B. (2010). Impact caps: Why population, a- uence and technology strategies should be abandoned, Journal of Cleaner Production. 18 (6): 552–560. doi:10.1016/j.jclepro.2009.08.001

[2] Barbier, E.B. (2012): A Global Green New Deal, Rethinking the Economic Recovery, Cambridge University Press, https://doi.org/10.1017/ CBO9780511844607

[3] Blanco G., R. Gerlagh, S. Suh, J. Barrett, H. C. de Coninck, C. F. Diaz Morejon, .. and P. Zhou (2014): Drivers, Trends and Mitigation. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Edenhofer et al. (eds.), Cambridge University Press, Cambridge, UK and New York, USA.

[8] See Dietz and Stern (2015), Dietz and Venmans (2019), and Bretschger (2020).

[4] Bretschger, L. (2020): Malthus in the Light of Climate Change, European Economic Review, in Press.

[5] Bretschger, L. (2013): Population Growth and Natural Resource Scarcity: Long-Run Development under Seemingly Unfavourable Conditions, Scandinavian Journal of Economics, 115/3: 722–755.

[6] Brock, W. and A. Xepapadeas (2017): Climate Change Policy under Polar Amplification, European Economic Review, 94: 263-282.

[7] Dietz, S. and N. Stern (2015): Endogenous growth, convexity of damage and climate risk: How Nordhaus'framework supports deep cuts in carbon emissions, Economic Journal 125: 574-620.

[8] Dietz, S. and F. Venmans (2019): Cumulative carbon emissions and economic policy: In search of general principles, Journal of Environmental Economics and Management, 96: 108-129.

[9] Dixit, A. and J. Stiglitz (1977): Monopolistic Competition and Optimum Product Diversity, American Economic Review, 67 (3): 297-308.

[10] Ebenstein, A. (2010): The 'Missing Girls'of China and the Unintended Consequences of the One Child Policy, Journal of Human Resources, 45(1): 87-115.

[11] Ehrlich, P.R. and J.P. Holdren (1971): Impact of Population Growth. Science 171 (3977): 1212–1217, doi:10.1126/ science.171.3977.1212.

[12] Gollier, C. and J. Tirole (2015): Negotiating effective institutions against climate change, Economics of Energy and Environmental Policy, 4(2): 1-32.

[13] Groth, C. and P. Schou (2002): Can non-renewable resources alleviate the knife-edge character of endogenous growth? Oxford Economic Papers 54: 386-411.

[14] Hesketh, T. (2009): Too many males in China: the causes and the consequences, Significance 6 (1): 9-13.

[15] Hotelling, H. (1931): The Economics of Exhaustible Resources, Journal of Political Economy, 39/2: 137-175.

[16] Kaldor, N. (1957): A Model of Economic Growth, Economic Journal, 67 (268): 591–624.

[17] Kaya, Y. and K. Yokoburi (1997): Environment, energy, and economy : strategies for sustainability. Tokyo [u.a.]: United Nations Univ. Press. ISBN 9280809113.

[18] Kremer, M. (1993): Population Growth and Technological Change: One Million B.C. to 1990, Quarterly Journal of Economics, 108/3: 681-716.

[19] McGlade, C. and P. Ekins (2015): The geographical distribution of fossil fuels unused when limiting global warming to 2 C, Nature 517: 187–190.

[20] Nakicenovic,N. J. Alcamo, G. Davis, B. de Vries, J. Fenhann,..Z. Dadi: (2000): Special Report on Emissions Scenarios, Working Group III of IPCC, University of Cambridge, Cambridge, UK.

[21] Nordhaus, W.D. (2017): Revisiting the social cost of carbon, PNAS, doi.org/10.1073/pnas.1609244114 .

[22] Peretto, P. and S. Valente (2015): Growth on a finite planet: resources, technology and population in the long run, Journal of Economic Growth, 20 (3): 305-331.

[23] Perman, R., Y. Ma, M. Common, D. Maddison and James McGilvray (2011): Natural Resource and Environmental Economics, Addison Wesley, 4th edition.

[24] Romer, P.M. (1990): Endogenous Technological Change, Journal of Political Economy 98/5: S71-S102.

[25] Schumpeter, J. (1912): Theorie der wirtschaftlichen Entwicklung, Berlin.

Appendix: Theory

The IAT rule is derived from an economy in which, at each point of time t, a good i is produced in quantity x_i; labor L, capital K, and resources R are the inputs in production so that

$$x_{it} = L_{xit}^{\alpha} K_{it}^{\beta} R_{xit}^{1-\alpha-\beta}$$

where $0 < \alpha, \beta < 1$. To calculate total output Y as a function of all goods I use the well-known Spence-Dixit-Stiglitz approach[9] reading

$$Y_t = B \left[\int_0^{\tilde{T}_t} x_{i,t}^{\eta} di \right]^{\frac{1}{\eta}}$$

with $B > 0$ and $0 < \eta < 1$ so that output grows with increasing input quantities x and rising product variety $\tilde{T}$, reflecting the gains from diversification, an important driver of economic growth. I define $\kappa \equiv (1-\eta)/\eta$ and use a symmetrical equilibrium where goods have equal production costs so that $x_{it} = x_t$ and $X_t = \tilde{T}_t x_t$ which leads to

$$Y_t = B\tilde{T}_t^{\kappa} X_t = B\tilde{T}_t^{\kappa} L_{Y,t}^{\alpha} K_t^{\beta} R_{Y,t}^{1-\alpha-\beta}. \tag{9}$$

Taking the log differential of Eq. (9) yields output growth as a function of the growth rates of the inputs; output per capita is given by $\hat{Y} = \widehat{Y/L} + \hat{L}$. To satisfy the stylized facts

[9] Dixit and Stiglitz (1977)

of Kaldor for long-run growth[10] I assume a balanced growth path with constant savings rate (leading to $\hat{Y} = \hat{K}$) and constant sectoral input shares ($\hat{L}_{Y,t} = \hat{L}_t$, $\hat{R}_{Y,t} = \hat{R}_t$) so that

$$\begin{aligned} \widehat{Y/L} + \ \hat{L} &= \kappa g + \alpha \hat{L} + \beta \left(\widehat{Y/L} + \hat{L} \right) + (1-\alpha-\beta)\hat{R} \\ \widehat{Y/L} \ &= \frac{1}{1-\beta} \left[\kappa g - (1-\alpha-\beta)\,\hat{L} + (1-\alpha-\beta)\hat{R} \right]. \end{aligned} \tag{10}$$

From Eq. (10) one can see that technical progress ($g > 0$) raises per capita growth and that labor growth ($\hat{L}$) has a negative impact reflecting the resource demand effect. We could add a consumer demand side of the economy and solve for consumption growth, which is equal to income growth in steady state, but this is not needed in this context. As explained in the main text I add the supply effect of labor on technology following Paul Romer; the education of labor is ignored here for simplicity, one can assume that research labor is trained on the job which adds a cost markup in the research lab which does not affect the growth rates of the variables used here (see Bretschger 2020). In the Romer model (Romer 1990) research labs invent new goods varieties i which causes proportional spillovers to public knowledge so that knowledge growth with labor and resource as inputs in the research sector becomes

$$g_t = \ L_{T,t}^{\gamma} R_{T,t}^{1-\gamma} \tag{11}$$

where $0 < \gamma < 1$. In steady state we have a constant innovation rate ($\hat{g} = 0$) and constant sectoral input shares ($\hat{L}_{T,t} = \hat{L}_t$, $\hat{R}_{T,t} = \hat{R}_t$) so that

$$0 = \gamma \hat{L} + (1-\gamma)\hat{R} \Leftrightarrow \hat{L} = -\frac{1-\gamma}{\gamma}\hat{R}$$

which is inserted in Eq. (10) so that per capita output growth results in

$$\widehat{Y/L} \ = \frac{1}{1-\beta} \left[\kappa g + \left(\frac{1-\alpha-\beta}{\gamma} \right) \hat{R} \right]. \tag{12}$$

Solving for $\hat{R}$ yields Eq. (7) in the main text where $\Phi = \frac{\gamma(1-\beta)}{1-\alpha-\beta}$ and $\Psi = -\frac{\kappa\gamma}{1-\alpha-\beta}$ and integrating gives the IAT formula in the main text i.e. Eq. (6) where C is the constant of integration. The model can be completed as follows. Given a politically determined resource path (fixing $\hat{R}$), Eq. (11) shows that the growth of the labor force allows to calculate innovation growth. To explain this growth of the labor force i.e. population development using first principles, theories of fertility and mortality have to be employed[11] and calibrated for the purpose. Endogenous population growth complements the climate economic analysis by making innovation and innovation growth endogenous variables.[12]

[10] Kaldor (1957)

[11] See Peretto and Valente (2015) and Bretschger (2013).

[12] See Bretschger (2020) for the details.

Appendix: Figures 3-6

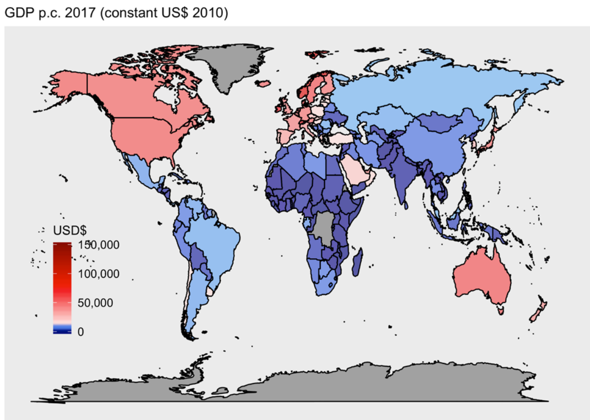

Figure 3. GDP per capita (2017)

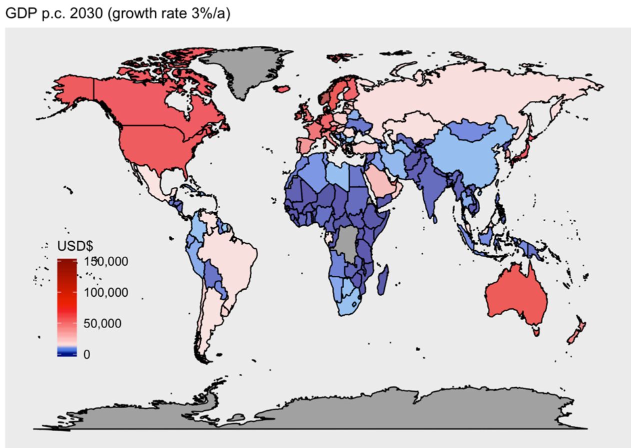

Figure 4. GDP per capita (2030) IPAST

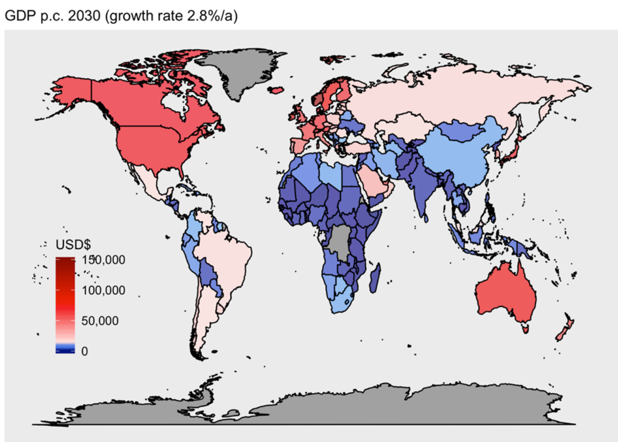

Figure 5. GDP per capita (2030) IAT

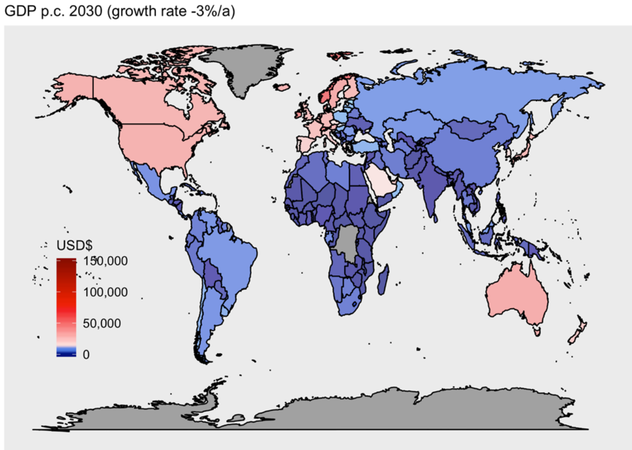

Figure 6. GDP per capita (2030) IPAT

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