

Twenty First Century Economic Slowdown and Its Impact on CO₂ Emissions
in the United States

By:
John Patrick Shapland
University of Colorado Boulder

A thesis submitted to the
University of Colorado Boulder
in partial fulfilment
of the requirements to receive
Honors designation in Environmental Studies
Fall 2019

Thesis Advisors:
Matthew Burgess, Environmental Studies
Daniel Kaffine, Economics
Dale Miller, Environmental Studies

©2019 by John Shapland
All rights reserved

Abstract

There is an emerging consensus among the academic community that United States economic growth will slow over the next century. However, there is an uncertainty regarding how quickly or by how much growth will slow. This project analyzes the effects of possible slowdowns in GDP per-capita growth on CO₂ emissions. The Shared Socioeconomic Pathways (SSPs) forecast slowdowns in economic growth based on assumptions made by the various SSP narratives. This project compares SSP growth forecasts with one of the more pessimistic projections offered by Robert Gordon. Gordon predicts that GDP per-capita growth will slow to the rate of 0.2% per-year (lower than any of the SSPs forecast). The methodology of this thesis creates modified SSPs based on Gordon's growth projections to analyze the impact of slowing economic growth on CO₂ emissions. The result of this analysis suggests that slower growth in the Middle of the Road scenario (SSP2) will lead to a reduction of carbon emissions by half as much in 2100 as the reduction from shifting to the sustainability scenario (SSP1). The implication of Gordon's economic projections could have a sizable impact on emission reduction, one comparable to significant changes to the energy sector.

Table of Contents

Abstract.....	ii
Preface and Acknowledgement.....	1
Introduction.....	2
Background.....	3
Gordon’s Four Headwinds.....	4
Techno-optimists.....	6
SSP 1 Narrative: Sustainability.....	7
SSP 2 Narrative: Middle of the Road	7
SSP 5 Narrative: Fossil Fueled Development.....	8
Economic Assumptions Based on SSP Narratives	8
Methodology.....	11
Results.....	13
Discussion.....	15
Conclusion	17
References:.....	19

Preface and Acknowledgement

This project uses gross domestic product (GDP), population, and emission projections for the United States created by the Shared Socioeconomic Pathways and Robert Gordon. It aspires to encourage future research on the impact of economic growth on carbon emission levels. There is much to understand in order to avoid the most drastic climate change scenarios. Thank you to all of those who believed in me and encouraged the completion of this thesis. I want to thank my primary advisor, Matthew Burgess, and Honors Council representative, Dale Miller, for their constant support and help along the way.

Introduction

The past two centuries have seen immense economic growth and a rising rate of environmental degradation. The question remains whether the decoupling of economic growth and anthropogenic ecological damage (e.g., CO₂ emissions) is possible. Leading economists widely agree that rates of economic growth will decline in the next century (Christensen et al., 2018); however, there is a significant disagreement on how quickly or by how much economic growth will slow.

The wide range of projected temperature changes in climate models does not solely stem from uncertainty in temperature change. Instead, the range of projections is due to different socioeconomic scenarios. This difference is the cause of much of the uncertainty about changes in future climate conditions. The Shared Socioeconomic Pathways (SSPs) attempt to conceptualize these uncertainties, by providing a scenario framework that aids in climate research. (Riahi et al., 2017). There are five SSPs, each based on an individual narrative that assumes key socioeconomic developments. Each SSP creates economic growth and CO₂ projections based on these assumptions. This project focuses on SSP1 (Sustainability), SSP2 (Middle of the Road), and SSP5 (Fossil Fueled Development). SSP2 is a business as usual scenario and is most plausible given its conventional assumptions. SSP1 represents a lofty target scenario aimed at sustainability. Discussion is given to SSP5 because it is useful as a reference for a worst-case scenario (Riahi et al., 2017).

Robert Gordon (2016) theorizes that U.S. economic growth is permanently slowing, and he has especially pessimistic forecasts of growth compared with others (see Christensen et al., 2018). Gordon claims that four economic headwinds will slow American growth: aging demographics, a plateau in educational attainment, income inequality, and rising debt. Therefore,

the U.S. would need a tremendous amount of technological innovation to offset this slowdown. Gordon (2016) also argues that future innovations cannot be as transformative to the economy as those seen in the 20th century. Due to less impactful innovation and the four headwinds, Gordon predicts that per-capita GDP growth will slow to 0.2% per-year by the end of the 21st century, substantially lower than any of the SSPs forecasts. Raising the question of what impact such slowdowns in growth will have on carbon emissions.

This project aspires to conceptualize and estimate the magnitude of declining per-capita GDP growth on CO₂ emissions in the United States. To do this, I manipulated data made by the Shared Socioeconomic Pathways (Riahi et al., 2017). I replaced economic growth predictions made in the SSPs with growth trajectories designed to be consistent with Gordon's (2016) forecast. Then, I estimated the impact on carbon emissions due to these revised economic scenarios.

Background

This section will provide the background knowledge needed to understand the information within this project. It will examine the foundation behind Robert Gordon's (2016) theory that American economic growth is permanently declining. Additionally, a brief introduction is given to Gordon's critics, which are more optimistic about technology, referred to as "techno-optimists". Lastly, a briefing on the assumptions made in each SSP narrative will be provided. Each narrative is constructed around two key socioeconomic drivers, challenges to mitigation and challenges to adaptation (Riahi et al., 2017). For example, emission without policies is an indicator of difficulties for mitigation. Vulnerability to climate change is an index of problems associated with adoption. The SSP narratives guide the economic assumptions made in each economic model.

Gordon's Four Headwinds

Despite the introduction of future innovations, Gordon (2016) argues that the U.S. economy will face four headwinds that will inevitably inhibit potential growth in productivity (usually measured as output per of factor of production or per worker) and therefore reduce GDP per-capita growth.

The first of the four headwinds is an aging demographic. The retirement of baby boomers will reduce hours worked per-capita. Retirees stay in the population while contributing few hours of market work. Creating a difference between productivity growth and output per-capita growth. Additionally, between 1965 and 1990, the number of women entering the workforce increased dramatically. Greater gender diversification in the workplace made hours per-capita increase, which allowed per-capita GDP to grow at a faster rate than output per-hour. However, women can only enter the workforce once, and, today, the baby-boomer generation is starting to retire. Retirees are no longer included in the total hours worked; yet, they are still included in the total population. Therefore, hours per-capita is declining, and output per-capita inevitably will grow at a slower rate than productivity (Gordon, 2016).

The second headwind is a plateau in educational attainment. The percentage of the U.S. population receiving tertiary education peaked in the late 1980s and has held roughly steady ever since (Golden, 2008). The plateau in educational attainment directly decreases the growth of labor productivity and results in slower growth of per-capita output (Gordon, 2016). The U.S. is falling in its international rank in the percentage of its population that achieves a university degree (Montez et al., 2012). Not only is the U.S. falling behind other advanced countries regarding higher education, but also in its ranking of primary school. Out of the 37 member nations of the Organization for Economic Co-operation and Development (OECD), the U.S.

ranked 21st in reading and writing, 31st in math, and 34th in science (Addonizio, 2015).

Education has been a central driver of growth throughout the 20th century, and less education directly reduces productivity growth. Plateauing education translates to slower growth in per-capita output--thus, slower productivity growth (Gordon, 2016).

The third headwind is income inequality. The median income has risen at a substantially lower rate than average per-capita income. Moreover, the average annual growth in household incomes was 1.3% from 1993 to 2008, well below increases in the Consumer Price Index (i.e., household purchasing power declined). For the 99% of income earners, the annual wage growth rate was only 0.75%, 0.55% below average increases in income. In contrast, the top 1% of income earners received more than half of all income gains from 1993 to 2008. High-income individuals spend smaller fractions of their income relative to low-income individuals. This disparity in spending is the primary mechanism that slows growth (Dynan et al., 2004). Income inequality not only affects output per-capita, but it also limits the majority of American from accessing the average per-capita GDP growth (Gordon, 2016).

Gordon's final headwind is the accumulation of private and governmental debt. In 2015, American households suffered from a debt burden of 133% of disposable income. Rapidly rising costs of homes, college, and health care, combined with increases in credit card debt, contribute to increased amounts of private debt (Markoff, 2014). Federal government debt has also significantly increased in the past decades to 104% of GDP as of 2019 (The Federal Reserve, 2019). There is a mix of economic policies that can be used to lower the ratio of government debt to GDP: raising taxes, decreasing expenditures, or lowering entitlement benefits (e.g., raising the retirement age or reducing access to welfare programs). However, increased taxes and lower entitlement transfers will decrease the growth rate of the disposable income of households

relative to GDP. This headwind is the result of the need to raise tax rates and reduce the growth of transfer payments to place the government's budget on a sustainable long-run growth trajectory. This headwind decreases the growth of disposable income relative to pre-tax or pre-transfer income (Gordon, 2016).

Techno-optimists

Techno-optimists foresee an acceleration of innovation faster than any previous period of rapid technological change. They claim a boom in future innovation will overpower Gordon's four headwinds, and productivity growth will continue as it has in the past two centuries. A central theme of the techno-optimists has been that measures of GDP growth underestimate the consumer surplus created by open access to information on the Internet. Techno-optimists argue that technological change is accelerating (Brynjolfsson and McAfee, 2014). However, a significant flaw in assessing this optimistic view is that there is rarely an examination of past times of technological change. Techno-optimists seldom provide time horizons of the acceleration or specific numbers. They offer only a general estimation of the rise of artificial intelligence and the geometric growth of big data processing capacity. Additionally, productivity growth data suggests that technological change is slowing, not accelerating. The post-1972 pace of technological change peaked in 1996-2000 (the dot.com boom), and has been slowing down since then (Gordon, 2016).

SSP 1 Narrative: Sustainability

This narrative has low challenges to mitigation and adaptation to climate change (Riahi et al., 2017). This scenario suggests a relatively high growth of global GDP per-capita combined with a reduced reliance on natural resources (e.g., fossil fuels). This is achieved by rapid technological change and high levels of international cooperation to address climate change. This narrative assumes a rise in educational attainment and reduced fertility rates, thereby slowing the growth of the global population. Globally, industrial societies shift to a more sustainable path that emphasizes inclusive development and respects ecological boundaries. This narrative reflects an improvement in the management of the world's common pool resources, expediting investments in health and education, and an emphasis on economic growth in terms of improving human wellbeing. Global inequality decreases as a result of an increased commitment to reach development goals. There is a significant reduction in the consumption of material, natural resources, and energy due to improvements in efficiency.

SSP 2 Narrative: Middle of the Road

This narrative has moderate challenges to mitigation and adaptation to climate change (Riahi et al., 2017). For the most part, current trends continue with mild progress made toward global GDP per-capita convergence. Global social, economic, and technological trends continue on their current trajectory. Income and development growth will continue unevenly. International and national efforts work slowly to achieve sustainable development goals, and environmental degradation continues. Overall energy and resource intensity declines, while population growth is moderate and plateaus in the latter half of the century. Income inequality improves slowly, but challenges persist in decreasing vulnerability to social and environmental changes. Some

emerging economies catch up relatively quickly, but growth is much slower in the least developed nations. Global CO₂ emissions will follow the current trends of decreasing slowly.

SSP 5 Narrative: Fossil Fueled Development

This narrative has immense challenges to mitigation and low challenges to the adaptation to climate change (Riahi et al., 2017). Nations place focus on economic development without regard to environmental degradation. Societies place a large amount of faith in the concept of competitive markets. Innovations will lead to rapid technological advances. The world marketplaces grows increasingly interdependent, and there are increased investments in health, education, human and social capital. However, economic development remains dependent on fossil fuels. Energy and resource intensive lifestyles continue, and there is rapid global economic growth. Global population peaks and then declines in the latter half of the century. Environmental hazards are successfully managed by new technology.

Economic Assumptions Based on SSP Narratives

The SSPs use a combination of three economic growth models. The OECD ENV-Growth model (Dellink et al., 2017), IIASA GDP model (Crespo Cuaresma et al., 2017), and PIK GDP-32 model (Leimbach et al., 2017) utilize the same demographic projections to maintain consistent assumptions of education and population. The economic models differ in terms of their focus on distinct drivers of economic development: technological change, progress in energy efficiency, and the dynamic of income convergence (or the accumulation of human capital). In order to ensure consistency, the SSP authors use the OECD-ENV Growth model as a baseline for the SSPs. In all SSPs, GDP per-capita growth is projected to slow with average growth rates in the latter half of the century to approximately 50% of rate in the first half.

Economic growth projections are based on the ENV-Growth modeling framework (Dellink et al., 2017). Growth projections began in 2018 after initially mimicking short-term (2015-2017) predictions of the OECD and the International Monetary Fund (IMF). Models assume each country will gradually catch up to its frontier level of GDP per-capita that is consistent with its endowment and institutions (Barro and Sala-i-Martin, 2004). GDP projections are made using an augmented Solow growth model that includes the accumulation of human capital and total factors of productivity (TFP) as the main drivers of growth. However, a limitation to the Solow model is that it assumes convergence begins immediately despite historical evidence that the timing of convergence is uncertain (Solow, 1956). This limitation is dealt with by modeling the short term economic forecasts by the OECD and IMF and by adopting a gradual transition towards the long term GDP per-capita growth. In addition to TFP, the models add human capital and elements in the projections of TFP that are specific to the U.S. Models assumes a slow convergence of capital-to-output ratios to a moderate long-term level. Additionally, this model includes energy both as an input for productivity (Foure et al., 2012) and as a generator of resource rents for fossil fuel producing countries (World Bank, 2012).

Higher education levels and slower population growth create low challenges for adapting to climate change, whereas a narrative with significant population growth and low education levels lead to more challenges for adaptation (Dellink et al., 2017). Furthermore, rapid technological development in SSP1 creates sustainability with fewer problems for climate change mitigation. On the other hand, SSP5 reflects considerable growth in carbon emissions due to the exploitation of fossil fuels and more challenges to climate mitigation.

Assumptions of future technological development and fossil fuel resources are altered to reflect SSP narratives (Dellink et al., 2017). Drivers of technology change are assumed to be

higher in narratives with international collaboration and more consideration for the environment. The rate of change of the technology frontier is a crucial driver for growth in the U.S. due to its leadership in technology and thus will be less dependent on convergence. The rate of change in the technology frontier is assumed to be the highest in SSP5, followed by SSP1. Likewise, the speed of convergence and trade openness are highest in SSP5.

Specific natural resource modules are created for each SSP for oil and gas usage assumptions related to energy prices and extraction rates (Dellink et al., 2017). These assumptions are based on the energy related component of each narrative. Narratives with higher energy demand, such as SSP5, have more challenges to mitigation. Additionally, narratives with high GDP per-capita growth include high energy demand, such as in SSP1 and SSP5. However, SSP1 is more focused on renewable energy sources rather than fossil fuels.

SSP GDP per-capita projections provide a basis for quantitative analyses of environmental impacts (Dellink et al., 2017); however, by themselves, they do not include any analysis of feedback from ecological effects on the economy. Yet, each SSP narrative assumes the same availability of fossil fuel resources as input for economic activity. GDP per-capita is presented in 2005 U.S. dollars using consistent purchasing power parity (PPP). Each SSP assumes that PPP exchange rates will gradually converge as productivity gains affect the overall structure of the U.S. economy. GDP per-capita growth is highest in SSP5.

Variations in GDP per-capita growth across SSPs are due to differences in the cumulative effects of economic drivers. Population has a dual role in projections since population growth can increase supplies of labor, but an aging population will shrink labor markets relative to the total population. Growing populations implies that total GDP is divided by more individuals. In

the first decades of the 21st century, capital accumulation and increases in TFP are the main drivers of growth in GDP per-capita growth for each SSP (Dellink et al., 2017).

Methodology

In this thesis I used U.S. population projections created by KC and Lutz (2016) and related GDP predictions generated by Dellink et al. (2017) (OECD ENV-Growth model), Crespo Cuaresma et al. (2017) (IIASA GDP model), and Leimbach et al. (2017) (PIK GDP-32 model). These data sets were used to calculate projected SSP GDP per-capita growth rates, starting from observed (2015) to 2100. I then generated a modified SSP by assuming (per Gordon 2016) that U.S. GDP per-capita growth will reach 0.2% per-year by 2100 under the narrative of SSP2. I refer to these modified Gordon SSPs as GSSPX corresponding to SSPX ($X = 1, 2, 5$). I assumed GSSP2 mimics the downward trajectory of SSP2, which is chosen because it makes the most ‘business-as-usual’ type assumptions, relative to SSP1 and SSP5. I interpolated growth in GSSP2 by assuming the percent difference between SSP2 and GSSP2 GDP per-capita growth is zero in 2015 and 0.54% in 2100 (the difference between SSP2 growth in 2100 and Gordon’s assumed growth of 0.2% averaged between the three economic models). I then assumed this percent difference interpolates linearly between 2015 and 2100. Then calculated the fractional difference between GSSP2 and SSP2 growth in 5-year interval, assuming per-capita GDP growth in other GSSP scenarios are the same fraction smaller than growth in the corresponding SSP (see Figure 1).

Next, I used SSP CO₂ emission forecasts created by six different emission models: AIM/CGE (Fujimori et al., 2016), GCAM (Calvin et al., 2016), IMAGE (van Vuuren et al., 2016), MESSAGE-GLOBIOM (Fricko et al., 2016), REMIND-MAgPIE, and WITCH-GLOBIOM (Kriegler et al., 2016). These six emission models project CO₂ emissions starting in

observed (2010) to 2100 for OECD member nations (Rao et al., 2017). To compute U.S. carbon emissions, I used observed emission data from 1990 to 2016 (OECD, 2019). The percentage of U.S. emissions of total OECD emissions stayed relatively constant between these years, varying less than three percentage points. Therefore, I assumed the share of U.S. emissions remained consistent at 42.7% to 2100 (see figure in Appendix 1).

I assumed that emission intensities ($\text{CO}_2/\text{dollar of GDP}$) are not affected by Gordon's pessimistic growth projections. In other words, GSSPX will have the same CO_2 -emission-intensity trajectory as SSPX. This assumption implies CO_2 emissions in GSSP scenarios are affected by the same proportion as the size of overall GDP is affected. The fractional difference between GSSPX and SSPX emissions is the same as the difference in GDP (Figure 2).

Results

Figure 1:

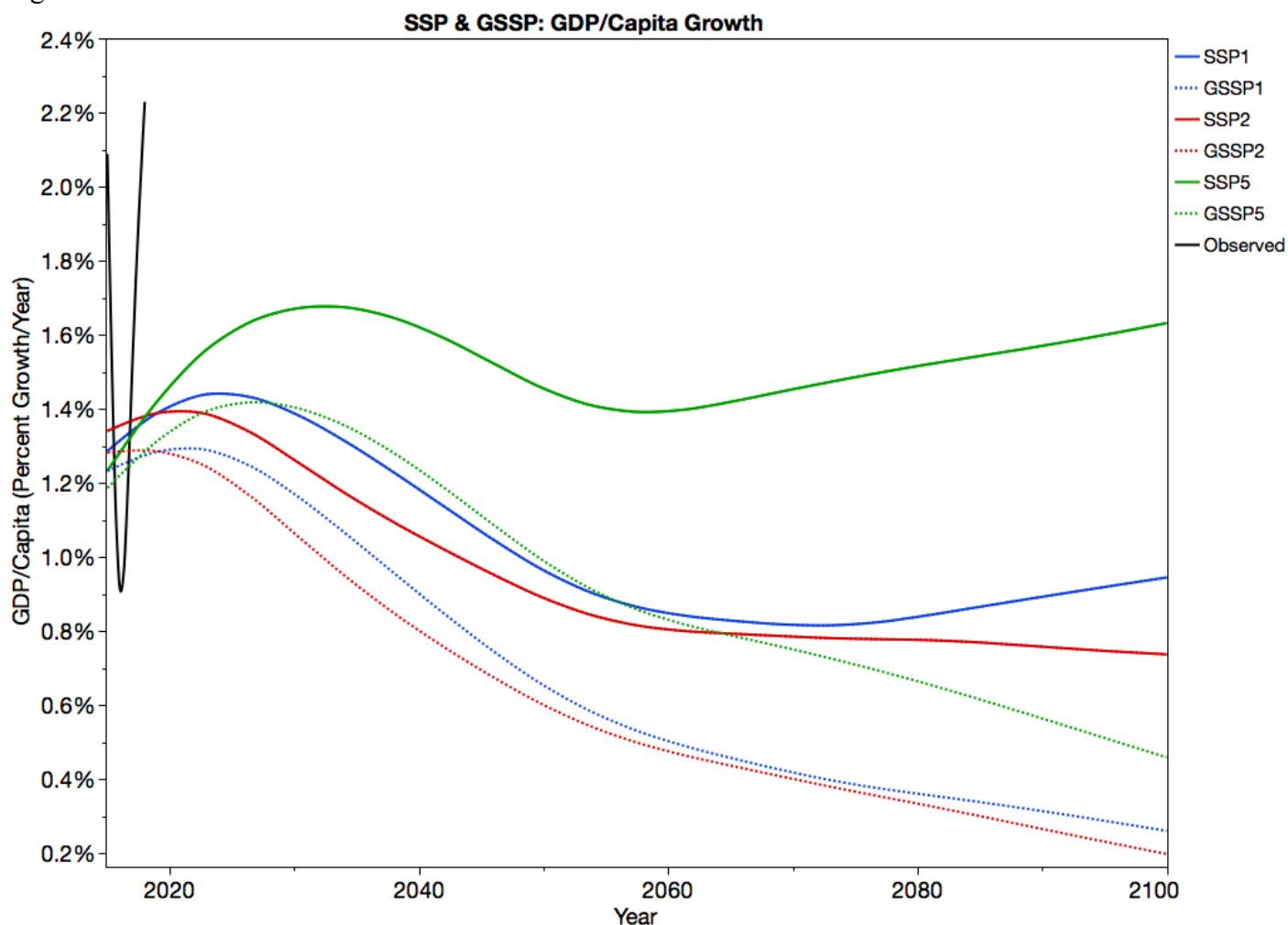


Figure 1 shows GDP per-capita growth projections from SSP1, SSP2, and SSP5 (solid lines) and modified GSSP1, GSSP2, and GSSP5 (dashed lines). Forecasts are in terms of percent growth/year starting in 2015 (observed) to 2100. The curve associated with SSPs and their corresponding GSSPs averages projections created by the three economic models using a smoothing spline. As reference, observed GDP/capita growth from 2015 to 2018 is graphed in black (World Bank, 2019).

Figure 2:

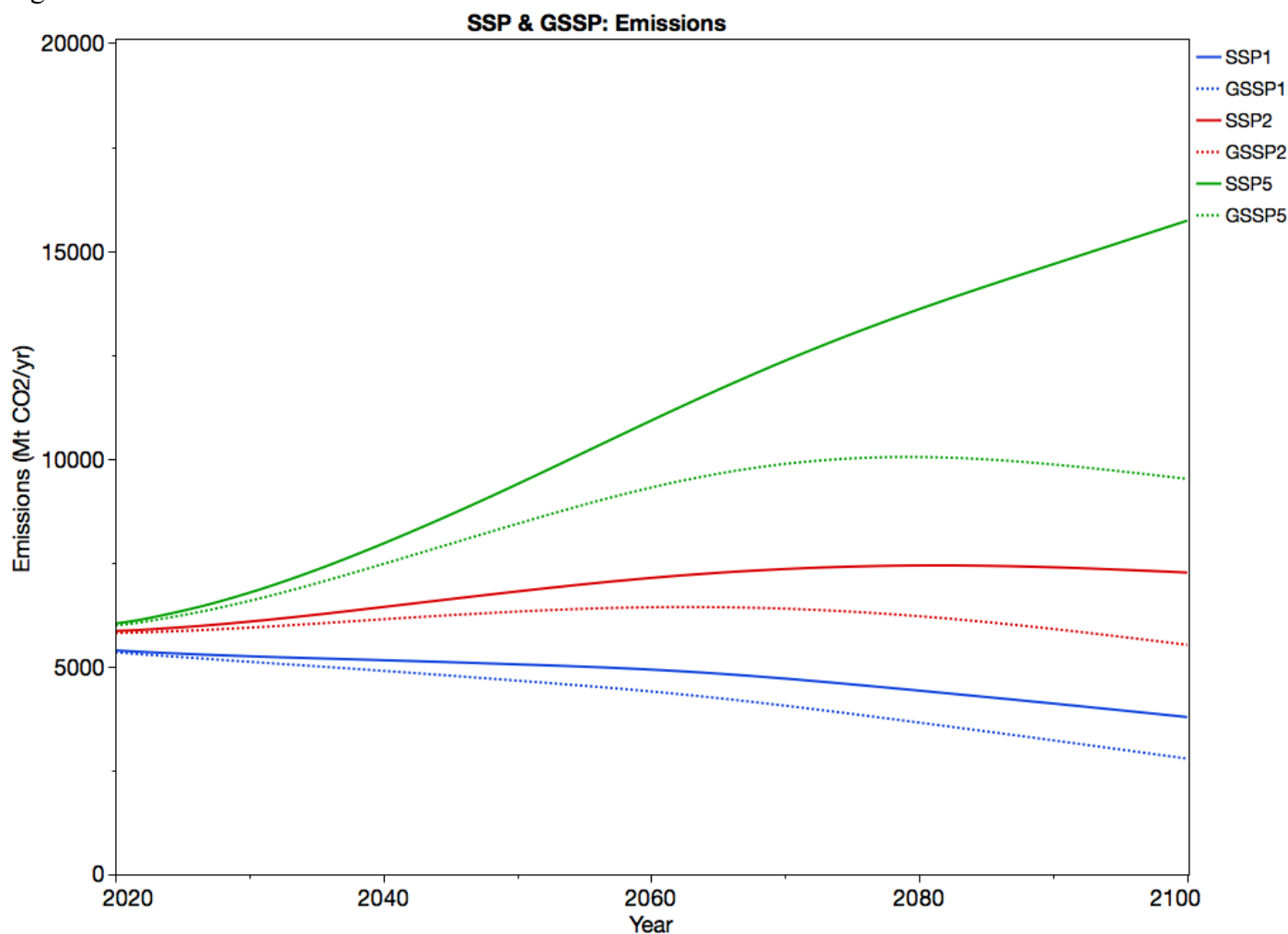


Figure 2 shows projected emissions for SSP1, SSP2, and SSP5 (solid lines) and modified GSSP1, GSSP2, and GSSP5 (dashed lines). Projections are given in terms of Mt of emitted CO₂/year starting from 2020 to 2100.

This analysis shows a difference of 0.54 annual percentage points between SSP2 and modified GSSP2 in 2100. Based on assumptions made by the narratives, there is an annual emission reduction of 3,463 Mt of CO₂ between SSP1 and SSP2 in 2100. The decrease in economic growth, based on Gordon's (2016) assumptions, results in a emission reduction of 1,735 Mt of CO₂ between SSP2 and GSSP2 in 2100. Therefore, a loss in GDP per-capita growth in GSSP2 results in a decrease in emissions about half as large as the reduction in emissions when moving from the Middle of the Road (SSP2) to Sustainability (SSP1). Thus, weak GDP

per-capita growth in Middle of the Road gets U.S. emissions approximately levels halfway (50.1%) closer to Sustainability levels.

Additionally, there is a difference of 1.17 percentage points annually between SSP5 (Fossil Fuel Development) and modified GSSP5 in 2100. Based on assumptions made by the narratives, there is an emission reduction of 11,970 Mt of CO₂ between SSP5 and SSP1 in 2100. The decrease in economic growth, based on Gordon's assumptions, results in an annual emission reduction of 6,248 Mt of CO₂ between SSP5 and GSSP5 in 2100. Weak GDP per-capita growth in SSP5 gets U.S. emissions levels slightly more than halfway (52.1%) closer to sustainability levels.

Discussion

This analysis shows slower GDP per-capita growth, in line with Gordon's predictions, reduces emission levels in the Middle of the Road (SSP2) by approximately half as much as those reflected in the sustainability scenario (SSP1). The result is a narrative where, if not much is assumed to change (i.e., business as usual), carbon emissions will be half as close to those of the Sustainability scenario (as defined by the SSPs) by 2100. Additionally, my results suggest Gordon's projection will move the worst-case scenario (SSP5) emissions more than halfway to the Sustainability scenario. Gordon (2016) argues that slowdowns in economic growth are unstoppable. Thus, the implications of Gordon's pessimistic growth projections could have a sizable effect on emission reduction that is on a similar order of magnitude to decarbonizing the energy sector (U.S. Department of Energy, 2017).

A central claim of ecological economics is that to achieve sustainability there must be a reduction in economic growth, implying that economic growth and rising overall emissions cannot be decoupled (Daly and Farley, 2004). Studies suggest climate caused decreases in

economic output, linked to increased global temperatures, are having a direct impact on population growth and labor productivity (Libecap and Stecke, 2011). Therefore, economic carbon cycles might decrease energy use and, thus, overall emissions. In contrast, increasing temperatures will increase demand for heating and cooling in commercial and residential sectors. Coupled with rising demands of electricity and transportation, energy efficiency will decrease, and carbon emissions will increase. In scenarios with the most temperature change have and decreases in economic growth have a 13% reduction in emissions in 2100. In contrast, the natural carbon-climate feedback will increase atmospheric CO₂ levels by approximately the same amount. The net impact of both feedbacks is almost net-carbon neutral (Woodard et al., 2018). Both this study and my own attempt to conceptualize the effects of potential changes in economic output on CO₂ emissions. A better understanding of the impacts of possible changes in economic growth on carbon emissions will improve the ability of nations to estimate restraints on cumulative emissions needed to meet specific emission reduction goals set forth by the Paris Climate Accord.

The purpose of this study was to project the effect of slowing growth on emissions, holding all else equal. My assumption that emission intensity of GDP is not affected by growth slowdowns in the GSSP scenarios is consistent with this objective. It is possible that slowing growth could impact emission intensity. If emission intensity increased as growth slowed then this would partially offset the projected reduction in emissions in my study.

Gordon provides no time horizon of growth slowdowns. Thus, I assume a path to 0.2% GDP per-capita growth by a simple interpolation that mimics growth projection created by the SSPs. This assumption impacts the final GDP per-capita in 2100, which is a critical determinant in final emission in this study. If growth declines were sharper in earlier years, GDP would be

lower and thus lower emission levels in 2100. In contrast, if growth declines were gradual in the first half of the century and sharper in the latter half, projected emission levels would be higher in 2100.

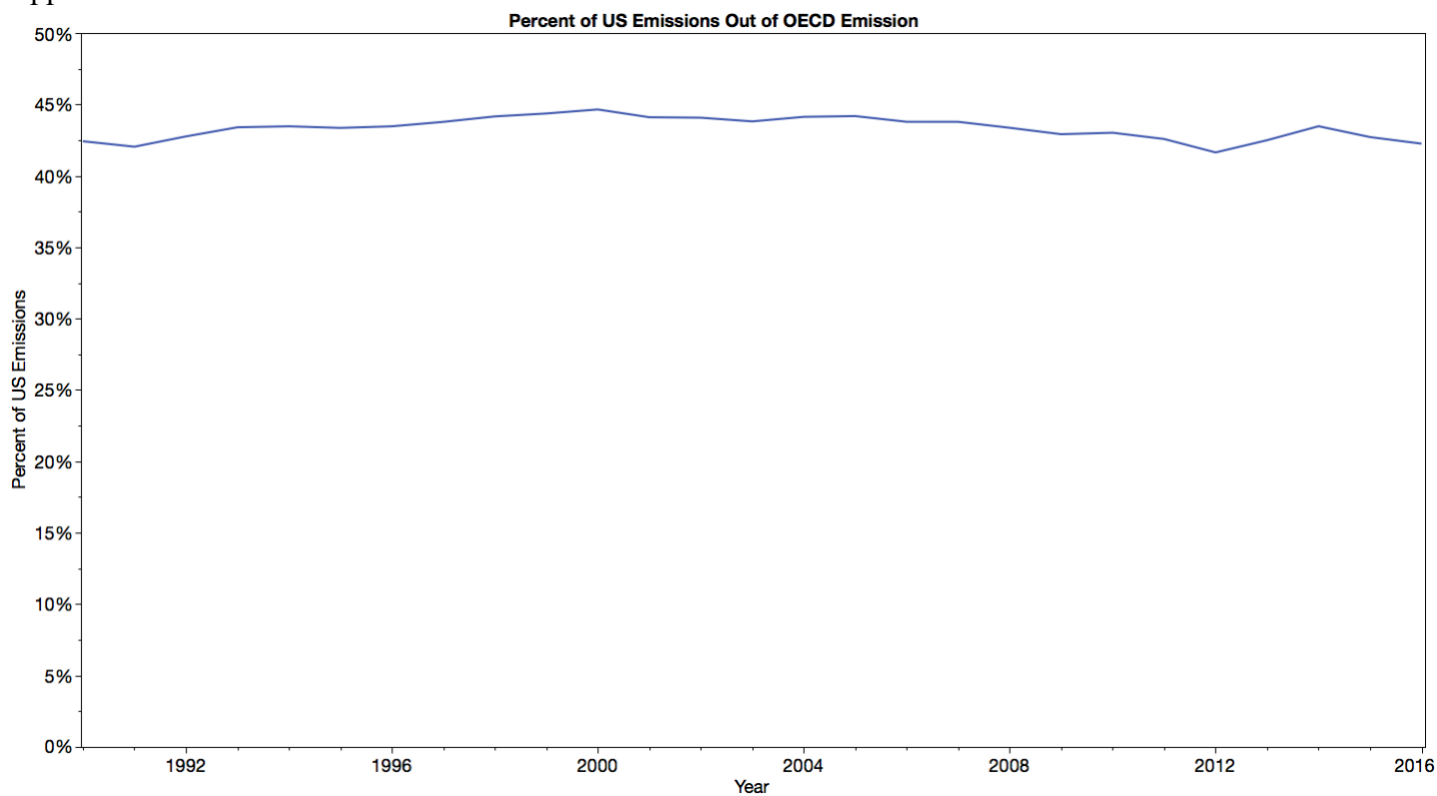
This study assumes that the U.S. fraction of OECD emissions stays constant at 42.7% throughout the next century (based on observed emission levels). In 1990, U.S. carbon emissions were 42.3% of total OECD emissions. While, at its height in 2000, U.S. emissions were 44.6% of OECD. Observed emission levels from 1990 -2016 have varied less than three percentage points of each other. Therefore, this analysis assumes emission levels will remain constant at average levels between the years 1990 and 2016.

Conclusion

There is widespread recognition of the need to reduce global CO₂ emissions to prevent catastrophic climate change scenarios. Emissions are ultimately determined by the size of the economy and its emission intensity. Some scholars and activists call for aggressive changes in both areas; rapid decarbonization of the economy and a halt to economic growth. Others have noted the significant challenges with such modifications, technologically in the case of decarbonization and politically in the case of economic growth. Gordon's (2016) analysis introduces the possibility of permanent reductions in growth as inevitability rather than a possibility. My study suggests that reductions in growth consistent with Gordon's analysis would reduce U.S. emissions substantially, compared with the SSP reference scenarios.

Appendix.

Appendix 1.



The graph above shows observed U.S. emission as a percent of total OECD emissions from 1990-2016. U.S. emissions stayed relatively constant, varying within 3 percentage points.

References:

- Addonizio, M. F., & Kearney, C. P. (2015;). Education reform and the limits of policy: Lessons from michigan. Kalamazoo: W.E. Upjohn Institute for Employment Research.
- Barro, R., Sala-i-Martin, X., 2004. Economic Growth, 2nd ed. MIT Press, Cambridge, MA.
- Brynjolfsson, E., & McAfee, A. (2014). The second machine age: Work, progress, and prosperity in a time of brilliant technologies (First ed.). New York: W.W. Norton & Company.
- Calvin, K., Bond-Lambert, Ben, Clarke, Leon, Edmonds, James, Eom, Jiyong, Hartin, Corinne, Kim, Sony, Kyle, Page, Link, Robert, Moss, Richard, McJeon, Haewon, Patel, Pralit, Smith, Steve, Waldhoff, Stephanie, Wise, M., 2016. SSP4: A world of inequality. Global Environ. Change doi:<http://dx.doi.org/10.1016/j.gloenvcha.2016.06.010>.
- Christensen, P., Gillingham, K., & Nordhaus, W. (2018). Uncertainty in forecasts of long-run economic growth. Proceedings of the National Academy of Sciences of the United States of America, 115(21), 5409-5414. doi:10.1073/pnas.1713628115
- Crespo Cuaresma, J. (2017). Income projections for climate change research: A framework based on human capital dynamics. Global Environmental Change, 42, 226-236. doi:10.1016/j.gloenvcha.2015.02.012
- Daly, H. E., & Farley, J. C. (2004). Ecological economics: Principles and applications. Washington: Island Press.
- Dellink, R., Chateau, J., Lanzi, E., & Magné, B. (2017). Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environmental Change, 42, 200-214.
- Dynan, K., Skinner, J., & Zeldes, S. (2004). Do the rich save more? Journal of Political Economy, 112(2), 397-444. doi:10.1086/381475
- The Federal Reserve of St. Louis “Gross Federal Debt as a Percent of Gross Domestic Product” FRED, 26 July, 2019. Retrieved from <https://fred.stlouisfed.org/series/GFDGDPA188S>
- Fouré, J., Benassy-Qué ré, A., Fontagne, L., 2012. The Great Shift: Macroeconomic Projections for the World Economy at the 2050 Horizon. CEPII Working Paper 2012-03.
- Fricko, O., Havlik, Petr, Rogelj, Joeri, Riahi, Keywan, Klimont, Zbigniew, Gusti, Mykola, Johnson, Nils, Kolp, Peter, Strubegger, Manfred, Valin, Hugo, Amann, Markus, Ermolieva, Tatiana, Forsell, Nicklas, Herrero, Mario, Heyes, Chris, Kindermann, Georg, Krey, Volker, McCollum, David, L., Obersteiner, Michael, Pachauri, Shonali, Rao, Shilpa, Schmid, Erwin, Schoepp, W., 2016. SSP2: a middle -of -the -road scenario for the 21st century. Global Environ. Change doi:<http:// dx.doi.org/10.1016/j.gloenvcha.2016.06.004>.

Fujimori, S., Hasegawa, Tomoko, Masui, Toshihiko, Takahashi, Kiyoshi, Silva Herran, Diego, Dai, Hancheng, Hijioka, Yasuaki, Kainuma, M., 2016. AIM implementation of shared socioeconomic pathways. *Global Environ. Change* doi:<http://dx.doi.org/10.1016/j.gloenvcha.2016.06.009>.

Gordon, R. J. (2016). *The rise and fall of american growth: The U.S. standard of living since the civil war*. Princeton: Princeton University Press.

KC, S., Lutz, W., 2016. The human core of the Shared Socioeconomic Pathways: population scenarios by age, sex and level of education for all countries to 2100. *Global Environ. Change* doi:<http://dx.doi.org/10.1016/j.gloenvcha.2014.06.004>.

Kriegler, E., Bauer, Nico, Popp, Alexander, Humpenöder, Florian, Leimbach, Marian, Strefler, Jessica, Baumstark, Lavinia, Bodirsky, Benjamin, Hilaire, Jerome, Klein, David, Mouratiadou, Ioanna, Weindl, Isabelle, Bertram, Christoph, Dietrich, Jan-Philipp, Luderer, Gunnar, Pehl, Michaja, Pietzcker, Robert, Piontek, Franziska, Lotze-Campen, Hermann, Biewald, Anne, Bonsch, Markus, Giannousakis, Anastasis, Kreidenweis, Ulrich, Müller, Christoph, Rolinski, Susanne, Schwanitz, Jana, Stefanovic, M., 2016. Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. *Global Environ. Change* doi:<http://dx.doi.org/10.1016/j.gloenvcha.2016.05.015>.

Leimbach, M., Kriegler, E., Roming, N., & Schwanitz, J. (2017). Future growth patterns of world regions—A GDP scenario approach. *Global Environmental Change*, 42, 215-225.

Libecap GD, Steckel RH (2011) *The Economics of Climate Change: Adaptations Past and Present* (University of Chicago Press, Chicago).

Markoff, John (2014). "In 1949, He Imagined an Age of Robots," *New York Times*, May 21, D8.

Montez, J. K., Hummer, R. A., & Hayward, M. D. (2012). Educational attainment and adult mortality in the united states: A systematic analysis of functional form. *Demography*, 49(1), 315-336. doi:10.1007/s13524-011-0082-8

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., . . . Pacific Northwest National Lab. (PNNL), Richland, WA (United States). (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42(C), 153-168. doi:10.1016/j.gloenvcha.2016.05.009

Solow, R., 1956. A contribution to the theory of economic growth. *Q. J. Econ.* 70 (1) . U.S. Energy Information Administration, 2011a. *World Shale Gas Resources: An*

Initial Assessment of 14 Regions Outside the United States Washington.

United States Department of Energy. Office of Energy Efficiency and Renewable Energy, National Renewable Energy Laboratory (U.S.), & United States. Department of Energy. Office of

Scientific and Technical Information. (2017). *Electrification and decarbonization: Exploring U.S. energy use and greenhouse gas emissions in scenarios with widespread electrification and power sector decarbonization*. Washington, D.C; Oak Ridge, Tenn;: United States. Department of Energy. Office of Energy Efficiency and Renewable Energy

van Vuuren, D.P., Stehfest, Elke, Gernaat, David, Doelman, Jonathan, van Berg, Maarten, Harmsen, Mathijs, H-S, Lex, Daioglou, Vassilis, Edelenbosch, Oreane, Girod, Bastien, Kram, Tom, Lassaletta, Luis, Lucas, Paul, van Meijl, Hans, Müller, Christoph, van Ruijven, Bas, Tabeau, Andrzej, 2016. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environ. Change* doi:<http://dx.doi.org/10.1016/j.gloenvcha.2016.05.008>.

Vujović, T., Petković, Z., Pavlović, M., & Jović, S. (2018). Economic growth based in carbon dioxide emission intensity. *Physica A: Statistical Mechanics and its Applications*, 506, 179-185. doi:10.1016/j.physa.2018.04.074

World Bank, December 2012. *World Development Indicators 2012 Database*. World Bank.

World Bank, 2019. *World Development Indicators 2019 Database*. World Bank. Retrieved from <https://data.worldbank.org/indicator/NY.GDP.PCAP.KD.ZG?locations=US>

Woodard, D., Davis, S., & Randerson, J. (2019;2018;). Economic carbon cycle feedbacks may offset additional warming from natural feedbacks. *Proceedings of the National Academy of Sciences of the United States of America*, 116(3), 759-764. doi:10.1073/pnas.1805187115