Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia

BRIDGING THE ENERGY DIVIDE AND SECURING HIGHER COLLECTIVE WELLBEING IN A CLIMATE-CONSTRAINED WORLD

Aline Ribas

Tese de Doutorado apresentada ao Programa de Pós-graduação em Planejamento Energético, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Planejamento Energético.

Orientadores: Roberto Schaeffer
André Frossard Pereira de Lucena

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“Happiness is the meaning and the purpose of life,

the whole aim and end of human existence.”

Aristotle (ca. 350 B.C.)

“All things share the same breath - the beast, the tree, the man. The air shares its spirit with all the life it supports.”

Chief Seattle (1854)

"*Procuremos más ser padres de nuestro porvenir que hijos de nuestro pasado*."

Miguel de Unamuno (1864-1936)

“The earth offers enough for everyone’s need, not for everyone’s greed”

Mahatma Gandhi (1869-1948)

“Somos responsáveis por aquilo que fazemos, o que não fazemos e o que impedimos de fazer.”

Albert Camus (1913-1960)

“I call the transformed world toward which we can move ‘sustainable,’ by which I mean (...) a world that evolves, as life on earth has evolved for three billion years, toward ever greater diversity, elegance, beauty, self-awareness, interrelationship, and spiritual realization.”

Donatella H. Meadows (1941-2001)

To every human being that has yet to gain access to reliable, sustainable and modern energy, and/or attain *swasthya* (true wellbeing).

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Resumo da Tese apresentada à COPPE/UFRJ como parte dos requisitos necessários para a obtenção do grau de Doutor em Ciências (D.Sc.)

VENCENDO A INIQUIDADE ENERGÉTICA E ASSEGURANDO O AUMENTO DO BEM-ESTAR COLETIVO EM UM MUNDO COM LIMITAÇÕES IMPOSTAS PELO CLIMA

Aline Ribas

Abril/2017

Orientadores: Roberto Schaeffer
André Frossard Pereira de Lucena

Programa: Planejamento Energético

Não obstante os ganhos expressivos na quantidade de energia disponível obtidos ao longo dos últimos dois séculos, seus benefícios continuam a ser distribuídos de forma extremamente desigual. O vencimento dessa iniquidade contribui para aumentar ainda mais o desafio de se atingir a estabilização do clima. Essa tese se propõe a examinar uma eventual incompatibilidade entre esses dois objetivos. Para tanto, estima-se a quantidade de energia que seria necessária para assegurar o aumento do bem-estar global até meados do século a partir de regressões log-log e calcula-se as emissões de carbono correspondentes com base nas intensidades de emissões de diferentes cenários do modelo de avaliação integrada MESSAGE. Utiliza-se uma proxy de bem-estar humano selecionada entre indicadores alternativos ao PIB, abrangendo os três pilares do desenvolvimento sustentável.

Os resultados indicam que mesmo com a adoção de novas políticas e ações de mitigação, emissões associadas ao aumento do bem-estar em todas as regiões onde melhorias ainda são necessárias, as quais representam 78 por cento da população global, poderiam exceder em até uma vez e meia as quotas consistentes com a meta de estabilização abaixo de 2 ^{o}C e, ainda mais, no caso de metas mais rigorosas. Conclui-se que mudanças nas escolhas de estilo de vida nos países desenvolvidos, como transporte pessoal e dieta, poderão ser essenciais para permitir o incremento de emissões necessário para se assegurar o aumento de bem-estar coletivo no resto do mundo.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

BRIDGING THE ENERGY DIVIDE AND SECURING HIGHER COLLECTIVE WELLBEING IN A CLIMATE-CONSTRAINED WORLD

Aline Ribas
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Advisors: Roberto Schaeffer
André Frossard Pereira de Lucena

Department: Energy Planning

In spite of the impressive gains in available energy over the last two centuries, the associated benefits remain unevenly distributed. Bridging this divide only adds to the already daunting challenge of securing climate stabilization. This thesis examines the potential incompatibility between these two efforts by estimating the additional energy needed to secure higher collective wellbeing across the globe by mid-century based on regional energy elasticities of wellbeing derived from regressions using linear log-log models and by calculating the associated carbon emissions based on emission intensities obtained from different climate action scenarios of the integrated assessment model MESSAGE. A proxy measure for human wellbeing is selected from existing alternative aggregate indicators to GDP, encompassing all three pillars of sustainable development.

Results indicate that even with new climate policies and actions, emissions associated with higher wellbeing in all regions where improvements are still needed, which represent 78 percent of the global population, could still reach up to one and a half times estimated 2 degrees Celsius budgets, and even more so for lower temperature increase targets. Given the scale of the overall gaps, effective changes in lifestyle choices in advanced countries, such as those associated with home energy use, private travel, and diet, would be needed to make room for the additional emissions needed to secure higher collective wellbeing in the rest of the world.

Contents

1. Introduction 1

2. Energy use and human development: an overview 7
  - 2.1. Energy transitions: from hunter-gatherers to the first high-energy civilization . 7
  - 2.2. The energy divide: minimum thresholds and access to modern energy services 11
  - 2.3. Energy use in a climate-constrained world 17
    - 2.3.1. The climate stabilization challenge 18
    - 2.3.2. Carbon budgets and emissions pathways associated with the "2 °C target" 26
    - 2.3.3. Carbon impact of energy use 30
  - 2.4. The energy use-human development nexus: a literature overview 32
    - 2.4.1. Traditional focus on economic growth 32
    - 2.4.2. Recent interest in broader aspects of human development 36

3. Human wellbeing: concepts and measurements from a development perspective . 44
  - 3.1. Early conceptualizations: from material individualism to spiritual collectivism 45
    - 3.1.1. Hedonism: wellbeing as maximization of individual pleasure 46
    - 3.1.2. Eudaimonism: wellbeing as the actualization of human potentials 47
    - 3.1.3. Eastern conceptualizations: wellbeing through self-transcendence 48
  - 3.2. Modern conceptualizations: from economic growth to sustainability 51
    - 3.2.1. The predominant one-dimensional conceptualization centered on economic growth 52
    - 3.2.2. Multi-dimensional conceptualizations: seeking a coherent theory of wellbeing 54
  - 3.3. Traditional measurements: GNP, GDP, GNI 58
    - 3.3.1. A brief history of national income and product statistics 60
    - 3.3.2. Shortcomings of GDP as a measure of societal wellbeing 64
  - 3.4. New measurements: alternative indicators to GDP 70
    - 3.4.1. Aggregate indicators using the *replacing* GDP approach: HDI, HSDI, and HPI 74
    - 3.4.2. Aggregate indicators using the *adjusting* GDP approach: GPI, IEWB, SSI, and IWI 76

3.4.3. Aggregate indicators using the *supplementing* GDP approach: SPI 81
3.4.4. Barriers to the deployment of new measurements 82
4. Bridging the energy divide: a quantitative assessment 90
4.1. Selecting proxies for human wellbeing from alternative indicators to GDP.... 92
4.2. Data preparation and analysis... 94
4.2.1. Data collection 94
4.2.2. Regional aggregation 95
4.2.3. Dataset analysis.. 96
4.3. Projecting aggregate levels of human wellbeing into 2050.............................. 98
4.4. Correlating human wellbeing and energy consumption................................ 101
4.5. Estimating the additional energy needed and associated carbon emissions... 106
5. Results 109
5.1. Additional energy needed and associated emissions..................................... 109
5.1.1. In ASIA 110
5.1.2. In the Middle East and Africa (MAF).. 111
5.1.3. In Latin America (LAM)... 112
5.1.4. In Economies in Transition (EIT) 112
5.2. Wellbeing versus climate stabilization: comparing emissions pathways....... 113
5.2.1. Associated emissions under no-action scenario...................................... 113
5.2.2. Climate action scenarios 118
5.2.3. Associated emissions under Action as of 2020-500 scenario 118
5.2.4. Associated emissions under Action as of 2020-450 scenario 121
5.2.5. Associated emissions under Delayed action-500 scenario....................... 123
5.3. Wellbeing versus climate stabilization: assessing the gaps............................ 125
6. Analysis of results and recommendations 128
6.1. Answering question number 1: how much energy consumption, and its corresponding CO_2 emissions, would be needed to bridge the energy divide and enable the achievement of higher levels of collective wellbeing? 129
6.2. Answering question number 2: Would the existing carbon budgets be affected? 129
6.3. Answering question number 3: If so, what part(s) of the world would be mostly at risk? 130
6.4. Answering question number 4: what needs to be done to bridge the energy

divide and increase wellbeing while staying within existing carbon budgets? 130
6.5. Recommendations 132

7. Final remarks 137
7.1. Contributions and policy implications 137
7.2. Suggestions for future research 140

References 143

Appendix A – Table of selected studies on energy consumption, GDP growth, and CO_2 emissions 177

Appendix B – Table of key alternative indicators to GDP. 181

Appendix C – Table of key data and calculations. 182

Appendix D – Table of region categorization. 185

Appendix E – Comparison with previous quantification efforts. 187

Appendix F – Assessing the gaps in all regions (including OECD90). 190

List of Figures

Figure 1 - Timeline of energy eras and great transitions. 8

Figure 2 - Selected dimensions of human development (standard of living, knowledge, and longevity) and annual per capita energy consumption rate, 1870–2005. 12

Figure 3 - Selected dimensions of human development (standard of living, knowledge, and longevity) and annual per capita energy consumption rate: Absolute gaps between OECD countries and the rest of the world, 1870-2005. 14

Figure 4 - Global energy divide in annual per capita primary energy consumption rates. 15

Figure 5 - Primary energy consumption levels in the developing world. 16

Figure 6 - Radiative forcing of climate between 1750 and 2011 (in W/m^2). Solid lines provide the range of uncertainty (5 to 95 percent confidence). 20

Figure 7 - Atmospheric carbon dioxide concentrations (in ppm) and global temperature anomalies (in ^{o}C) over the years 1880 to 2015. 22

Figure 8 - Simulated global mean surface temperature increase as a function of cumulative total global CO_2 emissions and cumulative emissions budget associated with the 2 ^{o}C target. 27

Figure 9 - Saturation and decoupling trend between HDI and carbon emissions (upper plot, 115 countries) and between HDI and energy consumption (114 countries for 1990 data and 116 countries for 2000 data and 2010 data) from 1990 to 2010. 39

Figure 10 - Income (in per capita GDP) versus wellbeing. 68

Figure 11 - Timeline of Key Alternative Indicators to GDP. 73

Figure 12 - Selection process for the appropriate proxy(ies) for human wellbeing. 92

Figure 13 - Observed changes in energy consumption measured in per capita primary energy consumption (*pcEC*), in wellbeing measured in per capita IWI (*pcIWI*), in income measured in per capita GDP (*pcGDP*) and in HDI for the overall sample between 1990 and 2010. 97

Figure 14 - Observed trends and projections (faded lines) of human wellbeing measured in per capita IWI (*pcIWI*) contrasted with observed trends and projections (faded lines) of per capita GDP (*pcGDP*). 100

Figure 15 - Correlation between human wellbeing measured in per capita IWI and energy consumption measured in per capita primary energy over the one hundred and eighteen countries covered here for the year 2000 (shown in log-log space).102

Figure 16 - Correlations of human wellbeing measured in per capita IWI (*pcIWI*) and energy consumption measured in per capita energy consumption (*pcEC*) in log-log form across four of the RC5 regions in the year 2010.. 104

Figure 17 - Change in elasticity *(b* values) over time... 105

Figure 18 - Estimated annual primary energy and CO_2 emissions pathways for achieving higher levels of human wellbeing in ASIA, EIT, LAM, and MAF, compared to two stabilization scenarios from the IAM MESSAGE (Immediate action-450 and Immediate action-500), which would yield reasonably high and even chances of achieving 2°C, respectively.. 115

Figure 19 - Estimated cumulative primary energy and CO_2 emissions for achieving higher levels of human wellbeing in ASIA, EIT, LAM, and MAF in 2011-2030 and 2011-2050, compared to two standard benchmark policy scenarios from the IAM MESSAGE v.4 (Immediate action-450 and Immediate action-500), which are associated with reasonably high and even chances of meeting the 2 °C target, respectively... 116

Figure 20 - Estimated annual primary energy and CO_2 emissions for achieving higher levels of human wellbeing in ASIA, EIT, LAM, and MAF in the Action as of 2020-500, compared to projections based on two stabilization scenarios from the IAM MESSAGE (Immediate action-450 and Immediate action-500), which would yield reasonably high and even chances of achieving 2°C, respectively............. 120

Figure 21 - Estimated annual primary energy and CO_2 emissions for achieving higher levels of human wellbeing in ASIA, EIT, LAM, and MAF in the Action as of 2020-450, compared to projections based on two stabilization scenarios from the IAM MESSAGE (Immediate action-450 and Immediate action-500), which would yield reasonably high and even chances of achieving 2°C, respectively............. 122

Figure 22 - Estimated annual primary energy and CO_2 emissions for achieving higher levels of human wellbeing in ASIA, EIT, LAM, and MAF in the Delayed action-500 scenario, compared to projections based on the stabilization scenarios from the IAM MESSAGE (Immediate action-450 and Immediate action-500), which would yield reasonably high and even chances of achieving 2°C, respectively............. 124

List of Tables

Table 1 - Selected non-market valuation methods applied to ecosystem services. 86
Table 2 - Key data values by year and region. 96
Table 3 - Per capita IWI across all RC5 regions in 2010 and projected to 2030 and 2050. 99
Table 4 - Regression results from Equation [1]... 103
Table 5 - Compound annual rates of change (%) in elasticity..................................... 106
Table 6 - Compound annual rates of change (%) in CO_2 emission intensity. 108
Table 7 - Annual results from Equations [3] and [4]... 109
Table 8 - Cumulative results from Equations [3] and [4].. 110
Table 9 - Emissions scenarios. 118
Table 10 - Compound annual rates of change (%) in CO_2 emission intensity on the Action as of 2020-500. 119
Table 11 - Compound annual rates of change (%) in CO_2 emission intensity on the Action as of 2020-450. 121
Table 12 - Compound annual rates of change (%) in CO_2 emission intensity on the Delayed action-500 scenario. 123
Table 13 – Wellbeing emissions shortfall by 2050 per emissions scenario compared to the 450-ppm budget. 126
Table 14 – Wellbeing emissions shortfall by 2050 per emissions scenario compared to the 500-ppm budget. 126

List of Tables in Appendices

Table A 1 - Selected studies on energy consumption, GDP growth, and CO_2 emissions. 177

Table B 1 - Key alternative indicators to GDP... 181

Table C 1 – Description of key data and calculations. 182

Table D 1 - Region categorization.. 185

Table F 1 - Emissions shortfall by 2050 per emissions scenario compared to the 450-ppm budget. 190
Table F 2 - Emissions shortfall by 2050 per emissions scenario compared to the 500-ppm budget. 191

List of Acronyms

ANS − Adjusted Net Savings
AR − Assessment Report
BCE − Before Common Era
BECCS − Bioenergy with carbon capture and storage
BP − British Petroleum
BRICS − Brazil, Russia, India, China and South Africa
CBA − Cost-Benefit Analysis
CCS − Carbon Capture and Storage
CDR − Carbon Dioxide Removal
CE − Common Era
CEC − Commission of the European Communities
CH_4 − Methane
CMEPSP − Commission on the Measurement of Economic Performance and Social Progress
CO_2 − Carbon Dioxide
CO_2eq − Carbon Dioxide Equivalent
COP − Conference of the Parties
CSLS − Centre for the Study of Living Standards
CSP − Concentrated Solar Power
DAC − Direct Air Capture
EBPT − European Biofuels Technology Platform
EC − Energy Consumption
EEA − European Environment Agency
EIT − Economies in Transition
EJ − Exajoule
FCCC − Framework Convention on Climate Change
GDP − Gross Domestic Product
GHG − Greenhouse Gases
GJ − Gigajoule
GNH − Gross National Happiness
GNI − Gross National Income

GNP − Gross National Product
Gt – Gigaton
GPI − Genuine Progress Indicator
HDI − Human Development Index
HLY − Happy Life Years
HPI − Happy Planet Index
HSDI − Human Sustainable Development Index
IAM − Integrated Assessment Model
IAMC − Integrated Assessment Modeling Consortium
IEA − International Energy Agency
IEAGHG − IEA Greenhouse Gas R&D Programme
IEG − International Evaluation Group
IEWB − Index of Economic Wellbeing
IHDP − International Human Dimensions Programme
IIASA − International Institute for Applied Systems Analysis
IMF − International Monetary Fund
INDC − Intended Nationally Determined Contribution
IPCC − Intergovernmental Panel on Climate Change
IRENA − International Renewable Energy Agency
ISEW − Index of Sustainable Economic Welfare
IWI − Inclusive Wealth Index
koe − Kilogram oil equivalent
kV − Kilovolts
kW − Kilowatt
kWh − Kilowatt-hour
LAM − Latin America
LIMITS − The Low climate Impact scenarios and the Implications of required Tight emission control Strategies
MAF − Middle East and Africa
MEA − Millennium Ecossystem Assessment
MESSAGE − Model for Energy Supply Systems And their General Environmental impact
MEW − Measure of Economic Welfare
MW − Megawatt

N_2O – Nitrous Oxide
NEF – New Economics Foundation
NOAA – National Oceanic and Atmospheric Administration
OECD – Organisation for Economic Co-operation and Development
ppm – parts per million
PPP – Purchase Power Parity
PV – Photovoltaics
RC – Region Categorization
RCP – Representative Concentration Pathways
RF – Radiative Forcing
SD – Sustainable Development
SEDA – Sustainable Economic Development Assessment
SNA – System of National Accounts
SPI – Social Progress Index
SSF – Sustainable Society Foundation
SSI – Sustainable Society Index
TAB – Threshold Avoidance Budget
TEB – Threshold Exceedance Budget
UN – United Nations
UNDP – UN Development Programme
UNEP – UN Environmental Programme
UNESCAP – UN Economic and Social Commission for Asia and the Pacific
UNESCO – United Nations Educational, Scientific and Cultural Organization
UNFCCC – UN Framework Convention on Climate Change
UNGA – UN General Assembly
UNU – University of the United Nations
USD – United States Dollar
W/m^2 – Watt per square meter
WCED– World Commission on Environment and Development
WEO – World Energy Outlook
WG – IPCC Working Group
WHO – World Health Organization
WMO – World Meteorological Organization
WTA – Willingness to Accept

WTP – Willingness to Pay

WVS – World Values Survey

ZEP – Zero Emission Fossil Fuel Power Plants

1. Introduction

Energy has played a vital role in humanity's struggle for subsistence as an essential input for food production, heat generation, and access to modern energy services. It also became a key component in several aspects of human development and wellbeing, such as educational opportunities, general health improvement, and food security (MARTINEZ AND EBENBACK, 2008). It has been deemed indispensable for eradicating poverty and inequality and achieving sustainable development (WCED, 1987; UNGA, 2015), a concept that postulates the existence of inextricable linkages among economic, social and environmental factors.

The origins of the link between energy use and human development can be traced straight back to the domestication of fire, the first extrasomatic energy conversion mastered by humans (SMIL, 2004), dated to some 500,000 years ago (JAMES *et al.*, 1989; CARBONNIER AND GRINEVALD, 2012). However, significant use of energy resources followed by technological progress leading to meaningful economic expansion did not start until around two centuries ago in a few European countries (SMIL, 2004), and continues to unfold in several developing countries.

Undoubtedly, the prosperity brought forth by the so-called thermo-industrial revolution has led, directly and indirectly, to remarkable improvements in the wellbeing of populations, notably healthier and longer lifespans, greater access to knowledge and formal education, and improved standards of living. Energy use has fostered economic growth, which, in turn, triggered demand for more and better-quality energy services. As such, energy use has gradually moved from low quality fuels to high quality fuels, from wood to coal, coal to petroleum, and petroleum to electricity.

The amount of energy consumed per capita in a society is said to be a good measure of its relative state of advance (WHITE, 1959 and ODUM, 1971). In average, the gross annual energy consumption per capita increased from about 10 gigajoules (GJ) at the time of the Roman Empire to about 15 GJ in 1700 (SMIL, 2008, 2010a, and 2011). By 1800, it had reached about 50 GJ in the United Kingdom alone, presumably the world's highest per capita energy consumption at the time (WARDE, 2007; cited in

SMIL, 2011). Then by 2010, it reached 135 GJ in the United Kingdom and an astounding 300 GJ in the United States.[1] Compared to 1900, the global average per capita energy consumption rate increased over fivefold, having reached 79 GJ by 2010.[2] It is noteworthy that these improvements are far more impressive when expressed in terms of actually available useful energy instead of gross primary energy inputs, in view of technical advances that have improved typical efficiencies of all principal commercial energy conversions over the last century (SMIL, 2000, 2010a, and 2011). According to SMIL (2000), the world had at its disposal at least twenty-five times more useful commercial energy in the year 2000 than in 1900.

In spite of the impressive gains in available energy over the last two centuries, the associated benefits remain unevenly distributed and a significant share of the world's population still dwells in energy poverty. By 2010, around 3 billion people, almost half of the world population, had an annual per capita primary energy consumption equal to or below 50 GJ, a rate that has been associated with a minimum quality of life (SMIL, 2010a), and still lacked access to basic modern energy services. In fact, more than one third of the world population enjoyed an average primary energy consumption rate equal to or even below 30 GJ, which is roughly one seventh the average energy use in affluent countries.[3] Moreover, almost 1 billion people are expected to be added to the population in the least developed part of the world by 2050 (UN, 2015), where annual primary energy consumption rates fall below 15 GJ per capita, on average.[4]

Meanwhile, the burning of increased quantities of coal and petroleum-based fuels has been the major cause of human induced climate change and is, therefore, considered the main contributing factor to the upward trend in Earth's surface temperature since 1950 (IPCC, 2014a). Annual carbon dioxide (CO_2) emissions from fossil fuel combustion for energy production and use have increased over 100 percent since 1970, in spite of the significant reductions in the CO_2 intensity of energy consumption seen in

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[1] Based on 2010 energy use data from the World Development Indicators (WORLD BANK, 2016) in kilograms of oil equivalent (koe) per capita converted to billion Joules (GJ) using IEA's energy unit converter (OECD/IEA, 2016a).

[2] Based on 2010 energy use data from the World Development Indicators (WORLD BANK, 2016) and IEA's energy unit converter (OECD/IEA, 2016a).

[3] Based on a calculated average of 201 GJ/capita for OECD countries using 2010 energy use data from the World Development Indicators (WORLD BANK, 2016).

[4] Based on 2010 energy use data from the World Development Indicators (WORLD BANK, 2016).

the same period (BLANCO *et al*., 2014). They are expected to continue increasing in the near future, as fossil fuels are likely to remain the dominant sources of energy (CLARKE *et al*., 2014; OECD/IEA, 2015b).

Hence, it is clear that higher levels of energy consumption will be needed to bridge the energy divide and enable the achievement of higher levels of human wellbeing across the globe. However, at current decarbonisation rates and state of knowledge and technology, the corresponding CO_2 emissions associated with such additional energy levels could compromise internationally agreed efforts towards climate stabilization. In 2010, the Parties to the Climate Change Convention agreed that, in order to achieve the necessary climate stabilization, global average temperature increase should be limited to "below 2 degrees Celsius" (^{o}C) above pre-industrial levels (UNFCCC, 2010), the so-called "2 ^{o}C target".[5]

By December 2015, one hundred and eighty seven countries that accounted for over 96 percent of global CO_2 equivalent emissions in 2012 had submitted climate pledges (so-called "Intended Nationally Determined Contributions" [INDCs]) outlining carbon reduction targets based on post-2020 action (KNUTTI *et al*., 2016; ROGELJ *et al*., 2016a). However, according to recent studies (UNEP, 2015; ROGELJ *et al*., 2016a), in the absence of additional emission reduction efforts, the estimated carbon budgets associated with the 2 ^{o}C target could be consumed as soon as 2030, and emissions would equate to scenarios that limit global average temperature increase in excess of the intended 2 ^{o}C target (e.g. median of 3.2 ^{o}C by 2100 at a 66 percent chance) (ROGELJ *et al*., 2016a). In this context, the additional energy needed to achieve higher levels of collective wellbeing only adds to the already daunting challenge of securing climate stabilization.

In light of these considerations, answers to the following pressing questions should be sought:

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[5] This target was recently revised to "well below 2 ^{o}C" in the 2015 Paris Conference (UNFCCC, 2015).

1. How much energy consumption, and its corresponding CO_2 emissions, would be needed to bridge the energy divide and enable the achievement of higher levels of collective wellbeing?

2. Would existing carbon budgets associated with climate stabilization be affected?

3. If so, what part(s) of the world would be mostly at risk? And

4. What needs to be done to bridge the energy divide and increase wellbeing while staying within existing carbon budgets?

In spite of the extensive literature on the relationship between energy consumption and economic growth, measured in terms of Gross Domestic Product (GDP) (CHEN *et al.*, 2012; OZTURK, 2010), including a number of studies encompassing CO_2 emissions (OMRI, 2013), only a small number of studies has examined the relationship between energy consumption and human development beyond its economic dimension (PASTERNAK, 2000; SMIL, 2003, DIAS *et al.*, 2006; MARTINEZ AND EBENHACK, 2008; JACKSON, 2009; STEINBERGER AND ROBERTS, 2009 and 2010; SMIL, 2010a; COSTA *et al.*, 2011; MAZUR, 2011; PASTEN AND SANTAMARINA, 2012; RAO AND BAER, 2012; STEINBERGER *et al.*, 2012; STECKEL *et al.*, 2013; JORGENSON, 2014; UGURSAL, 2014; and LAMB AND RAO, 2015).

To the author's knowledge, only four studies have actually attempted to quantify the energy needed to achieve certain levels of human wellbeing, namely PASTERNAK (2000), COSTA *et al.* (2011), UGURSAL (2014), and LAMB AND RAO (2015). Of those, only COSTA *et al.* (2011) and LAMB AND RAO (2015) have effectively quantified the corresponding CO_2 emissions. Moreover, because these studies used the Human Development Index (HDI) or some of its components as proxy for wellbeing, they failed to encompass the third fundamental aspect of human development, the environmental dimension. Everything that humanity needs for its survival and wellbeing depends, either directly or indirectly, on the natural environment. Humans are part of the natural world and dependent on the use of natural resources to sustain their social and economic wellbeing. Hence, a thorough measure of human wellbeing should include not only the economic and social dimensions of human development, but also its environmental dimension.

This study aims to help overcome this shortcoming by selecting a potential proxy for human wellbeing that encompasses not only the economic and social dimensions of human development, but also its environmental dimension. The ultimate goal of this study is to provide an indication of whether meeting the urgent energy needs while enabling the achievement of higher levels of collective wellbeing would be consistent or conflict with climate stabilization efforts, while trying to answer the four pressing questions listed above.

To this end, it conducts a quantitative assessment and provides estimates of the additional energy consumption and corresponding carbon emissions that would be associated with higher levels of collective wellbeing in all regions where improvements are still needed, first assuming no new climate policies (no-action scenario) and therefore prevailing technologies and decarbonisation rates. It then assesses the impact that such emissions would have on estimated carbon budgets associated with achieving the 2 ^{o}C target in each region. Alternative scenarios are also considered, where new climate policies (action scenarios) are taken into consideration to determine whether and how some gaps could be closed.

This study is organized in seven chapters, including this Introduction. Chapter 2 presents a historical overview of the linkages between energy use and human development from foraging societies to the first high-energy civilization, followed by a presentation of key challenges associated with energy poverty as well as those associated with climate constraints, and concludes with an overview of the relevant literature on the linkages between energy consumption and human development.

Chapter 3 discusses the challenges associated with trying to define and measure wellbeing from a human development perspective, given its complex and multi-dimensional nature. It describes how GDP became the primary measure of societal development and wellbeing despite its shortcomings and provides an overview of several initiatives towards the development of alternative measurements.

Chapter 4 presents the quantitative assessment framework devised in order to estimate the additional energy needed to meet urgent energy needs while enabling the achievement of higher levels of collective wellbeing, as well as its associated carbon impact, assuming no new climate policies (no-action scenario) and prevailing technologies and decarbonisation rates.

Chapter 5 presents the results obtained and compares the estimated CO_2 emissions obtained with regional emissions pathways associated with a 2 ^{o}C target. It then revises the estimates based on three alternative climate action scenarios and assesses the corresponding emission shortfalls. Chapter 6 discusses the results, while attempting to provide answers to the four relevant questions and some recommendations. And Chapter 7 ends with final remarks, highlighting key contributions and policy implications of this study, as well as including suggestions on how the assessment proposed in this thesis could be further improved and/or expanded in future studies.

2. Energy use and human development: an overview

Energy has been vital for human development through its ability to stimulate economic growth, generate employment, advance knowledge and educational opportunities, and improve general health and wellbeing of populations (MARTINEZ AND EBENHACK, 2008). It is the basis for almost all economic activities and has been deemed indispensable for eradicating poverty and inequality and achieving sustainable development (UN, 2015; WCED, 1987), a concept that postulates the existence of inextricable linkages among economic, social and environmental factors.

This chapter renders a historical overview of this intrinsic relationship since pre-historic human history, followed by discussions on energy poverty and climate constraints, and a review of the empirical research on the linkages between energy consumption and human development to date.

2.1. Energy transitions: from hunter-gatherers to the first high-energy civilization

The origins of the link between energy use and human development can be traced straight back to prehistoric human history when humans relied primarily on somatic energy to secure food and improve shelter, followed by the domestication of fire, the first extrasomatic energy conversion mastered by humans (SMIL, 2004), dated to approximately 500,000 years ago (JAMES *et al.*, 1989; CARBONNIER AND GRINEVALD, 2012).[6] However, it was not until just two centuries ago that the relationship between energy and modern economic development, as we know it today, was sealed (FOUQUET, 2008; AYRES, 2009, cited in CARBONNIER AND GRINEVALD, 2012).

Energy historian Vaclav Smil divides human history into three distinct eras of energy use and highlights four major transitions in the type and intensity of energy use

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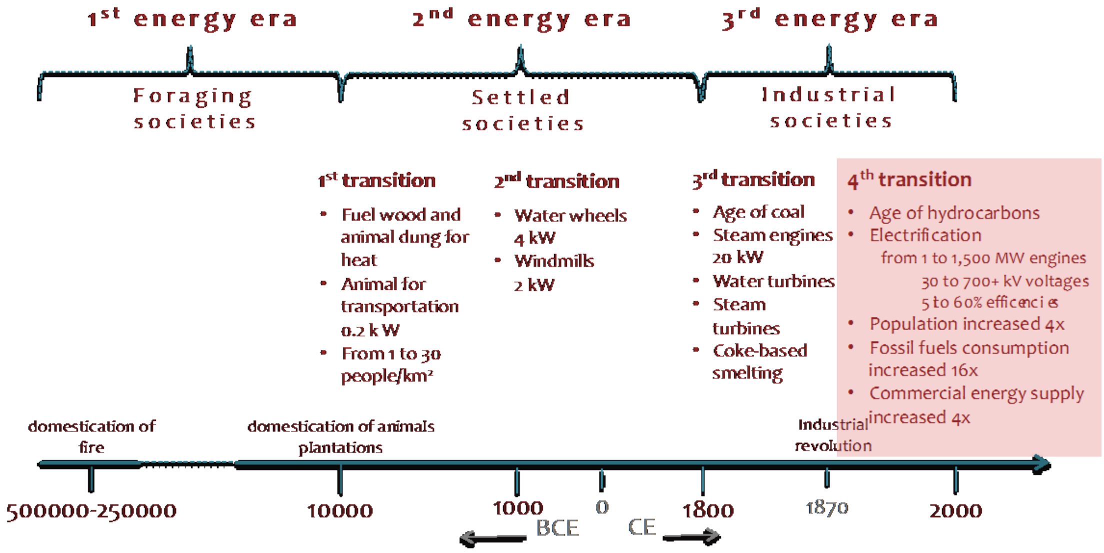
[6] While the earliest use of fire is still the subject of considerable debate, most archaeologists agree that it took place about 500,000 years ago. However, there has been evidence of fire use by early hominids in China approximately 1.7 million years ago (JAMES *et al.*, 1989).

(SMIL, 2004), as illustrated in Figure 1. In each transition the dominant methods of energy conversion are replaced and efficiencies in energy-dependent processes increased.[7]



Note: BCE refers to Before Common Era and CE to Common Era.

Figure 1 - Timeline of energy eras and great transitions.

Source: Prepared by the author based on SMIL (2004).

The first energy era encompasses prehistoric times of subsistence foraging (hunting and gathering) until the beginning of settled existence, which began shortly after the end of the last glacial period, about 10,000 years ago (SMIL, 2011). The shift from subsistence foraging to settled societies energized by cultivated plants and domesticated animals marked the beginning of the second energy era. This era lasted a few thousand years and staged the first and second energy transitions.

The first energy transition took place when humans started to domesticate animals (mostly oxen and horses) and use fire to produce metals and other durable materials, thereby raising energy throughput of pre-industrial societies by more than an order of magnitude (SMIL, 2004). Energy needs were then primarily met by burning of wood and dried animal dung for heat, wind power for water transportation, and animal power for land transportation and other jobs. The second energy transition took place

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[7] For a discussion on recent energy transitions in developed countries see O'CONNOR (2010).

during the first millennium Before Common Era (BCE)[8] as some societies substituted large shares of their animated prime movers by waterwheels and windmills, which converted water and wind, two common renewable energy flows with increasing power and efficiency to drive simple machines to ground grain and pump water. They remained the most powerful and reliable means to utilize energy for thousands of years, until the invention of the steam engine. Measured in modern terms, pre-industrial watermills would generate less than 4 kilowatt (kW) and windmills would generate up to 2 kW of power (SMIL, 2010b).

The third energy era coincided with the start of the third energy transition with the substitution of animate prime movers by engines and large-scale extraction and combustion of fossil fuels (SMIL, 2004 and 2010b). Fossil fuels seemed to be the perfect fuel source: energy-rich, dense, easily transportable and relatively straightforward to access (STEFFEN *et al.*, 2011). This era began only around 200 years ago in a few European countries, having been accomplished by all industrialized nations during the 20th century (SMIL, 2004), and continue to unfold in several developing countries albeit at different stages and following different paths.

Notably, one of the earliest signs of significant human use of high energy-intensive fossil fuels could be traced back to about a millennium ago during the Northern Song dynasty (960-1126 CE),[9] when the most impressive economic expansion took place in Imperial China (see HARTWELL, 1967). Developed primarily to support its iron and steel production, the coal industry grew in size between the ninth and the eleventh centuries to become equal to that of the entire Western Europe in the late 17th century. By the late 11th century, much of North China’s ore was being used in blast furnaces for smelting cast iron, replacing the up until then commonly used wood-derived charcoal (HARTWELL, 1967). However, the technological progress resulting from the close integration between coal and iron, which was later to be so crucial in the British industrial revolution, did not occur under subsequent Chinese dynasties

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[8] BCE is an abbreviation for "before the Common Era" (The American Heritage Dictionary of the English Language, s.v. “before the Common Era”, accessed December 20, 2016, https://ahdictionary.com/word/search.html?q=Common Era&submit.x=-761&submit.y=-210).

[9] CE is an abbreviation for “Common Era”, the period beginning with the traditional birth year of Jesus, designated as year 1 (The American Heritage Dictionary of the English Language, s.v. “Common Era”, accessed December 20, 2016, https://ahdictionary.com/word/search.html?q=Common Era&submit.x=-761&submit.y=-210).

(POMERANZ, 2000; WRIGHT, 2007).

The European coal industry, primarily in England, started to rise already in the 13th century, as coal became the fuel of choice in England while the rest of the world relied on wood and charcoal for their primary energy sources (STEFFEN *et al*., 2011). However, extensive coal use only started after James Watt made improvements to the steam engine in the late 1700s becoming a prime mover of unprecedented power suitable for many tasks (SMIL, 2004). Watt's engines averaged approximately 20 kW of power output, five times the performance of contemporary watermills (SMIL, 2004 and 2010b). A host of other innovative production methods and inventions sparked new pockets of industry, focusing on the production and use of large-scale machines rather than small hand tools, which have gradually replaced more and more human and animal labor.

Because it took energy to make machines work there was not only interest in using abundant and low-cost sources of energy but also in understanding how to get the greater work out of it. Therefore, 19th century scientists were encouraged to study the transformation of heat, a form of energy, to mechanical work and devise ways to get the most work from engines, leading to the rapid development of a whole new branch of natural sciences, namely thermodynamics (CARBONNIER AND GRINEVALD, 2011). It is based on two fundamental principles: the principle of energy conservation (known as the first law of thermodynamics) and the principle of energy dissipation or degradation (known as the second law of thermodynamics or "the entropy law").

Continuous technical innovation spurred impressive growth of capacities, flexibilities, and efficiencies of energy convertors, as well as advances in exploration, extraction, transportation, and transmission, which in turn paved the way to a demographic and scientific-technological explosion during the 20th century, primarily driven by growing levels of consumption of cheap and relatively abundant fossil fuels. Massive use of oil and natural gas, however, did not start until the early 1900s when large reserves were discovered. In fact, the rising global dependence on oil and gas and the process of electrification marked the fourth and greatest energy transition (SMIL, 2004).

Between 1900 and 2000, the electricity generation, transmission and distribution systems and the use of electricity saw impressive improvements in terms of capacity and efficiency rates, including enlargements from maximums of 1 to 1,500 megawatt (MW) turbogenerators, from less than 30 to more than 700 kilovolts (kV) alternate current transmission voltages, and from 5 to 40 percent thermal generation efficiencies (SMIL, 2004 and 2010a). A typical urban household in the United States saw its installed electric power increase sixty times, from less than 500 W (due to a few light bulbs) to upwards of 30 kW (with all electric gadgets and air-conditioning) in that same period (SMIL, 2000 and 2004). Meanwhile, despite the near quadrupling of global population, consumption of fossil fuels saw a sixteen-fold rise and the average annual per capita supply of commercial energy more than quadrupled, creating the first high-energy civilization in human history (SMIL, 2000).

2.2. The energy divide: minimum thresholds and access to modern energy services

The prosperity brought forth by the so-called thermo-industrial revolution has led, directly and indirectly, to remarkable improvements in the wellbeing of populations, notably healthier and longer lifespans, greater access to knowledge and formal education, and improved standards of living.

Historical trends indicate that energy transitions happened alongside higher levels of energy consumption (GRUBLER, 2004). Increased rates of energy consumption in turn have been extensively associated with higher levels of human development. The average annual energy consumption increased from no higher than 10 billion Joules (GJ) per capita during the Roman Empire to about 15 GJ in 1700 (SMIL, 2008, 2010a and 2011). By 1800, it had reached about 50 GJ in the United Kingdom alone, presumably the world's highest per capita energy consumption at the time (WARDE, 2007; cited in SMIL, 2011). Two hundred years later, it reached 135 GJ in the United Kingdom and an astounding 300 GJ in the United States.[10] Compared to 1900, the global average per capita energy consumption rate increased over fivefold

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[10] See footnote 1.

having reached 79 GJ by 2010.[11]

Even more impressive are the numbers associated with the increased supply of actually available useful energy,[12] as technical advances have improved typical efficiencies of all principal commercial energy conversions over the last century (SMIL, 2000, 2010a and 2011).[13] Conservative calculations in SMIL (2000) indicate that in the year 2000 the world had at its disposal about twenty-five times more useful commercial energy than it did in 1900. These up until then unprecedented gains translated into remarkable improvements in longevity (life expectancy at birth), knowledge (years of schooling) and standard of living (adjusted income) over the last one and a half century, and in particular over the decades that followed the Great Depression and the Second World War, as depicted in Figure 2.

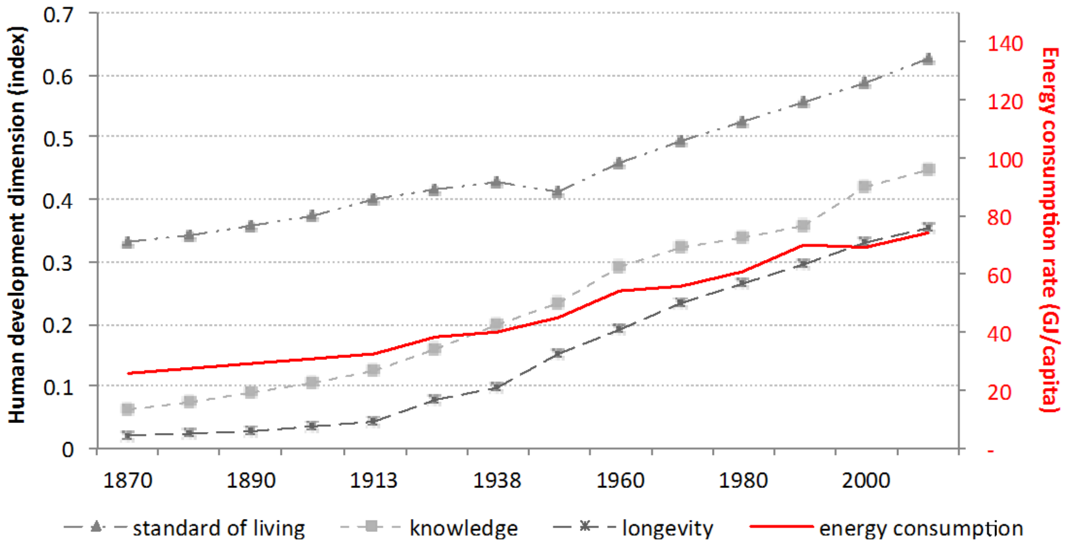

Figure 2 - Selected dimensions of human development (standard of living, knowledge, and longevity) and annual per capita energy consumption rate, 1870–2005.

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[11] See footnote 2.

[12] The portion of energy effectively made available to the user in terms of the services delivered after final conversion through end-user equipment (i.e. energy conversion devices). For instance, the chemical energy of gasoline can be converted to mechanical energy by an automobile. Similarly, electricity can be converted to thermal energy (heat) by an electric heater. According to the second law of thermodynamics or “the entropy law”, whenever energy is transformed, some amount of available energy is lost in the process (referred to “entropy”). Therefore the quantity of energy ultimately made available to the end-user depends on the actual efficiency rate of the conversion device used.

[13] Small coal-fired stoves in 1900 converted generally less than 20 percent of the fuel to useful heat, while the best natural gas–fired household furnaces in 2000 were up to 96 percent efficient (SMIL, 2000). Similarly, incandescent light bulbs with osmium filaments transformed less than 0.6 percent of electricity into light in 1900, while the best household fluorescent lights in 2000 were almost 10 percent efficient (SMIL, 2000).

Source: Prepared by the author based on human development data from (ESCOSURA, 2010), primary energy data pre-1970 from GRUBLER (2008) and from 1970 onwards from the World Bank's World Development Indicators (WORLD BANK, 2016).

Notwithstanding the impressive gains in available energy over the last two centuries, the associated benefits have been largely enjoyed only by a minority of the population living in the most advanced societies (about 18 percent based on 2010 data) and remain unevenly divided (see GRUBLER, 2004 and SMIL, 2004). Figure 3 depicts the widening gaps in energy consumption rates and selected dimensions of human development between advanced countries (represented here by OECD countries[14]) and the rest of the world. The absolute gap in average energy consumption rates has increased nine times since 1870, while those in human development dimensions up to five times.

At the outset of the period, the average per capita energy consumption rate among OECD countries was 41 GJ, less than double that of the rest of the world (25 GJ). By 2005, the OECD's average rate had reached approximately 177 GJ, over five times that of the rest of the world (40 GJ). Similarly, improvements in knowledge in OECD countries have far outpaced those in the rest of the world, particularly before the Second World War. Then, longevity doubled its gap between 1938 and 2005. Meanwhile, the gap in standard of living started to level off after 1980 and to retract after the year 2000.

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[14] The Organisation for Economic Co-operation and Development (OECD) is an international economic organization of 35 countries founded in 1961 to stimulate economic progress and world trade. Further information is available at: http://www.oecd.org/.

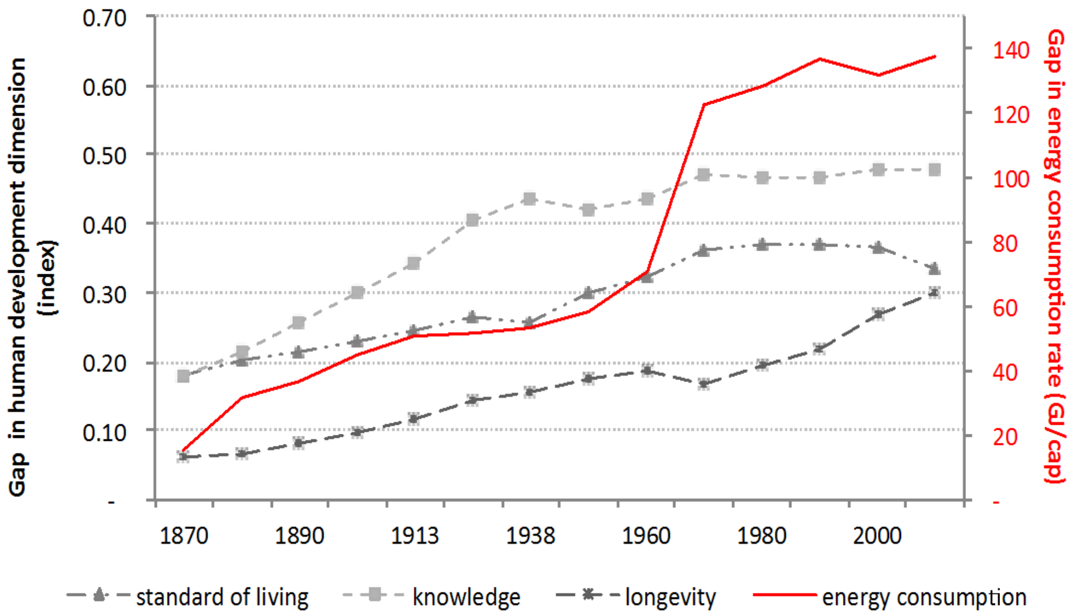

Figure 3 - Selected dimensions of human development (standard of living, knowledge, and longevity) and annual per capita energy consumption rate: Absolute gaps between OECD countries and the rest of the world, 1870-2005.

Source: Prepared by the author based on human development data from (ESCOSURA, 2010), primary energy data pre-1970 from GRUBLER (2008) and from 1970 onwards from the World Bank's World Development Indicators (WORLD BANK, 2016).

By 2010, over 3 billion people, representing almost half of the world population, had an annual per capita primary energy consumption equal to or below 50 GJ (Figure 4). In fact, more than one third of the world population endured an average primary energy consumption rate equal to or even below 30 GJ, which is roughly one seventh the average energy use in affluent countries.[15] [16] And the least developed part of the world endured an average rate that falls even below 15 GJ.[17] [18]

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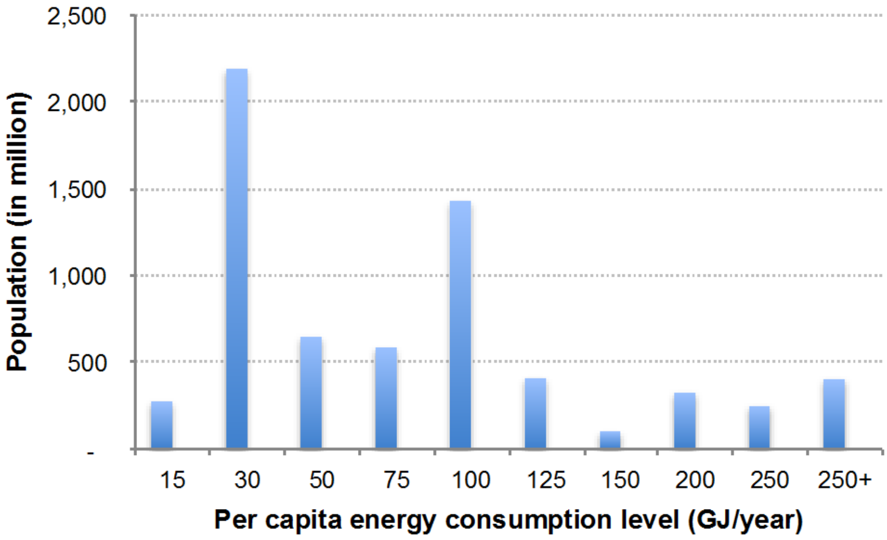
[15] See footnote 3.

[16] While the majority of affluent countries require a significant amount of energy for heating that may not be required in energy poor countries, the gap is still substantial.

[17] See footnote 4.

[18] The least developed part of the world refers to the group of countries that is classified by the United Nations as "least developed" in terms of their low-income levels and structural impediments to sustainable development.



Note: Each bar refers to the maximum rate achieved. For example, 15 GJ level refers to all rates up to 15 GJ.

Figure 4 - Global energy divide in annual per capita primary energy consumption rates.

Source: Prepared by the author based on 2010 data from the World Development Indicators (WORLD BANK, 2016).

Given that recent studies suggest that societies typically require an annual per capita primary energy consumption rate above 50 GJ (SMIL, 2010a) or 63 GJ (SPRENG, 2005) to be able to achieve decent living standards,[19] the numbers indicate that roughly half of the world population live in energy poor countries, where significant improvements in levels of wellbeing and development are still needed. When assessing the energy consumption rates within the developing part of the world, it becomes evident that energy poverty is primarily concentrated in Sub-Saharan Africa (all of Africa, except its Northern part) and Southern Asia (see Figure 5).

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[19] Notably, STEINBERGER AND ROBERTS (2009) argue that such threshold is not constant and actually decreases over time. Meanwhile, RAO AND BAER (2012) show that universal thresholds do not apply as each country has different circumstances.

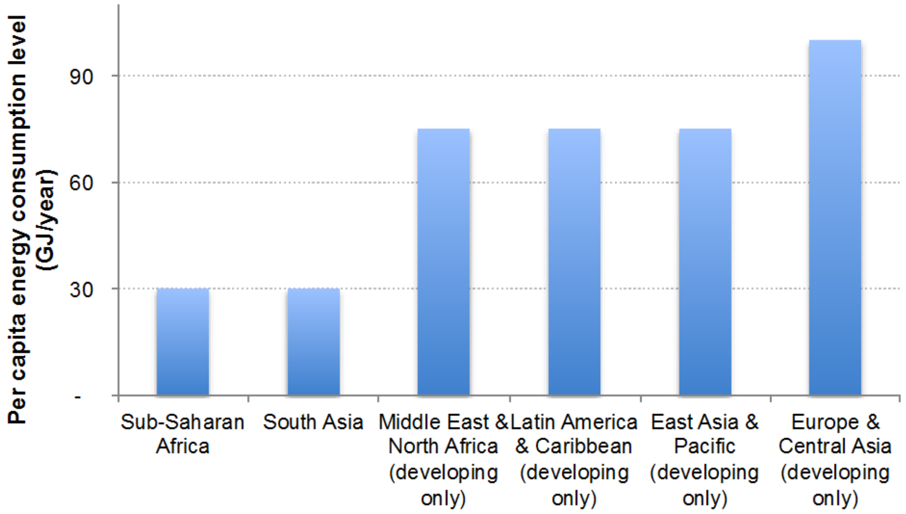

Figure 5 - Primary energy consumption levels in the developing world.

Source: Prepared by the author based on 2010 data from the World Development Indicators (WORLD BANK, 2016).

Besides low rates of primary energy consumption on a per capita basis, lack of access to modern energy services has also been associated with energy poverty. Access to modern energy services has been essential for human development and wellbeing, through the provision of clean water, sanitation, healthcare, reliable and efficient lighting, heating, cooking, transport, among other basic needs. It provides more efficient and healthier means to undertake basic household tasks and means to undertake productive activities, as well as drinking water through water pumping and increasing agricultural yields through the use of machinery and irrigation (OECD/IEA, 2015c), thereby enhancing competitiveness and promoting economic growth.

The so-called energy poor not only lack access to safe, clean fuels but rely mainly on traditional energy sources, such as animal dung, crop residues, and wood for cooking and heating (GOLDEMBERG *et al*., 2000), which cause harmful indoor air pollution. The World Health Organization estimates that more than 4 million people, primarily women and children, die prematurely each year from household air pollution due to inefficient biomass combustion based on 2012 data (WHO, 2016). Such inefficient cooking fuels and technologies not only produce environmental impacts but also high levels of household air pollution with a range of health-damaging pollutants, including small soot particles that penetrate deep into the lungs. In poorly ventilated dwellings, indoor smoke can be one hundred times higher than acceptable levels.

A significant share of the world's population still lacks access to basic modern energy services. By 2014, about 1.2 billion people (17 percent of the global population) still lacked access to electricity, with an additional billion "under-electrified" due to intermittency problems, which live predominantly in rural areas in sub-Saharan Africa or developing Asia (OECD/IEA, 2015c). Meanwhile, more than 2.7 billion people (38 percent of the world's population) are estimated to rely on the traditional use of solid biomass for cooking (OECD/IEA, 2015c). Sub-Saharan Africa and developing Asia once again dominate the global totals.

Approximately 80 percent of the additional population projected to be added to the world between 2015 and 2050, almost 2 billion people, are expected to occur in these regions (UN, 2015), almost half of which in areas with annual primary energy consumption rates below 15 GJ per capita, on average. Therefore, without significant improvements in energy access efforts, the absolute number of people with lower energy consumption rates and/or lacking any form of modern energy services, primarily electricity and clean cooking fuels and technologies (i.e. the "energy poor"), is bound to increase by mid-century (IEG, 2015). Yet, securing universal energy access and an energy consumption rate above the minimum threshold for decent living standards will be critical in order to bridge the energy divide and thereby enable further human development and, ultimately, the achievement of higher levels of collective wellbeing across the globe.

2.3. Energy use in a climate-constrained world

As shown in section 2.1 above, consumption of fossil fuels saw a sixteen-fold rise between 1900 and 2000 (SMIL, 2000). This impressive increase in consumption of fossil fuels, primarily coal and petroleum-based fuels, has been the main contributing factor to the upward trend in Earth's surface temperature since 1950 (IPCC, 2014a). Annual carbon dioxide (CO_2) emissions from fossil fuels combustion for energy production and use have increased over 100 percent since 1970, in spite of the significant reductions in the carbon intensity of energy consumption seen in the same period (BLANCO *et al.*, 2014). And they are expected to continue increasing in the near future, as fossil fuels are likely to remain the dominant sources of energy (CLARKE *et al.*, 2014; IEA, 2015b).

At current decarbonisation rates and state of knowledge and technology, the additional energy needed to bridge the energy divide and enable the achievement of higher levels of collective wellbeing only adds to the already daunting challenge of securing climate stabilization, as discussed below.

2.3.1. The climate stabilization challenge

The greenhouse effect is a natural phenomenon, essential for the existence of life on Earth given its critical role in regulating the overall temperature of the planet. It was first described by Joseph Fourier in 1827, experimentally verified by Claude-Servais-Mathias Pouillet in 1837, John Tyndall in 1865, and Samuel Pierpont Langley in 1888, then quantified and formally presented for the first time by Svante Arrhenius in 1896 (CRAWFORD, 1997; RODHE *et al.*, 1997; LACIS *et al.*, 2010).

By trapping Earth's surface heat, this effect allows the average temperature to remain around 14 ºC, which in turn allows for existence of life and makes the planet hospitable. Without this natural effect, Earth's surface would be covered with ice and its average temperature would be below the freezing point of water, lingering around -19 ºC (LE TREUT *et al.*, 2007). This effect is caused by the presence of certain gases in the atmosphere - water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrogen dioxide (N_2O), ozone (O_3), and fluorinated gases - that even though comprise about less than 1 percent of the dry atmosphere have more complex molecular shapes that trap heat allowing the atmosphere to act like a glass dome,[20] preventing that part of the infrared radiation reflected by the planet's surface returns to space (LE TREUT *et al.*, 2007; DESSLER AND PARSON, 2010). Due to their ability to trap heat in the same way as a greenhouse, these gases are denominated greenhouse gases (GHG).[21]

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[20] The two most abundant gases in the atmosphere, nitrogen (comprising 78 percent of the dry atmosphere) and oxygen (comprising 21 percent), do not absorb or emit infrared radiation, and therefore exert no greenhouse effect. (LE TREUT *et al.*, 2007; DESSLER AND PARSON, 2010).

[21] Svante Arrhenius referred to these gases as "selective absorbers" (RODHE *et al.*, 1997).

However, according to the scientific community and in particular to the International Panel on Climate Change (IPCC), established in 1988 by the World Meteorological Organization and the United Nations Environment Programme (RODHE *et al.*, 1997), atmospheric concentrations of noncondensing GHG,[22] mainly CO_2, CH_4, and N_2O, have increased substantially since 1750, as a result of anthropogenic activities (e.g. fossil fuel combustion, land use change, and agriculture). According to several reports of the IPCC's Working Group I (WGI), whose job is to assess the scientific information available, including its latest report as part of IPCC's Fifth Assessment Report (AR5) (IPCC, 2013a), human influence on the climate system became evident from, among other factors, the increasing concentrations of GHG in the atmosphere, in particular of CO_2, and observed increase in global average temperatures, primarily since the mid-twentieth century.

Changes in the atmospheric abundance of GHG are expressed in terms of radiative forcing (RF), which quantifies the alteration of Earth's energy budget caused by these gases (IPCC, 2014a). Positive RF values represent average near-surface warming and negative values represent average near-surface cooling. CO_2 is by far the largest single contributor to the total radiative forcing (see Figure 6). Net anthropogenic forcing is comparable to CO_2 forcing, given that positive non-CO_2 GHG (e.g. CH_4, N_2O, halocarbons) forcings tend to offset negative aerosol forcings (HANSEN *et al.*, 2008).

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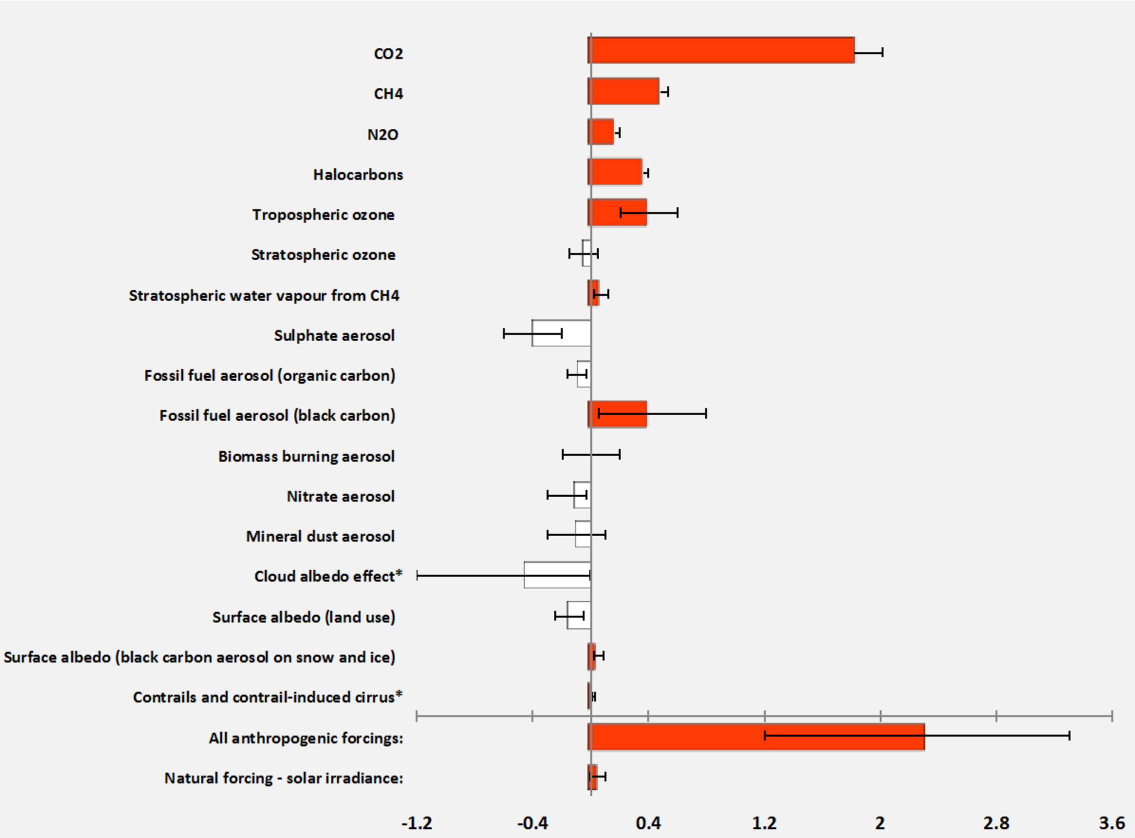
[22] Water vapor is not considered a climate-relevant greenhouse gas because it responds rapidly to changes in temperature and air pressure by evaporating, condensing, and precipitating (LACIS *et al.*, 2010).



Note: Effective radiative forcings (ERF) are used for cloud albedo effect and contrails.

Figure 6 - Radiative forcing of climate between 1750 and 2011 (in W/m^2). Solid lines provide the range of uncertainty (5 to 95 percent confidence).

Source: Prepared by the author based on data from MYHRE *et al*. (2013).

Moreover, CO_2 is far more abundant in the atmosphere as a large fraction of the CO_2 emitted stays in the atmosphere for centuries and longer (KNUTTI AND ROGELJ, 2015). While CH_4 and N_2O are removed from the atmosphere through chemical reactions,[23] CO_2 is redistributed among the different carbon reservoirs and ultimately recycled back to the atmosphere on a multitude of time scales (CIAIS *et al*., 2013). As atmospheric CO_2 concentrations rise, these exchange processes are altered. Depending on the additional amount of CO_2 released into the atmosphere, 20 to 40 percent remain in the atmosphere for more than five hundred years until a new balance in the global carbon cycle is reached (CIAIS *et al*., 2013; MYHRE *et al*., 2013).

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[23] It takes about one to two decades for CH_4 emissions to leave the atmosphere (it actually oxidizes and converts into CO_2) and about a century for N_2O (IPCC, 2014a).

Given the importance of atmospheric CO_2 concentrations, concerted efforts have been made towards its direct measurements since 1958 (see KEELING *et al*., 2005).[24] The carbon dioxide data from the Mauna Loa Observatory constitute the longest record of direct measurements of atmospheric CO_2 (NOAA, 2016a).[25] Data prior to 1958 are typically derived from ice cores like data from ETHERIDGE *et al*. (1996) derived from three ice cores obtained at Law Dome, East Antarctica, from 1987 to 1993. According to historical data from ETHERIDGE *et al*. (1996) and direct measurements from Mauna Loa (NOAA, 2016), atmospheric CO_2 concentration has increased by almost 40 percent from 290 parts per million (ppm) in 1880 to over 400 ppm in 2015. Notably, half of the rise occurred in the last three decades (see Figure 7).

The increased concentrations have enhanced the natural greenhouse effect causing unprecedented increases in global mean temperatures. The global annual temperature has increased at an average rate of 0.06 degrees Celsius (°C) per decade since 1880 and at an average rate of 0.25 °C per decade since 1970 (see Figure 6). Notably, the frequency of extreme high temperatures increased ten-fold between the first three decades of the last century and the first decade of the current century (see MUNASINGHE *et al*., 2012). December 2015 was the warmest month of any month in the 136-year period of record, at 1.11 °C higher than the monthly average (NOAA, 2016d).

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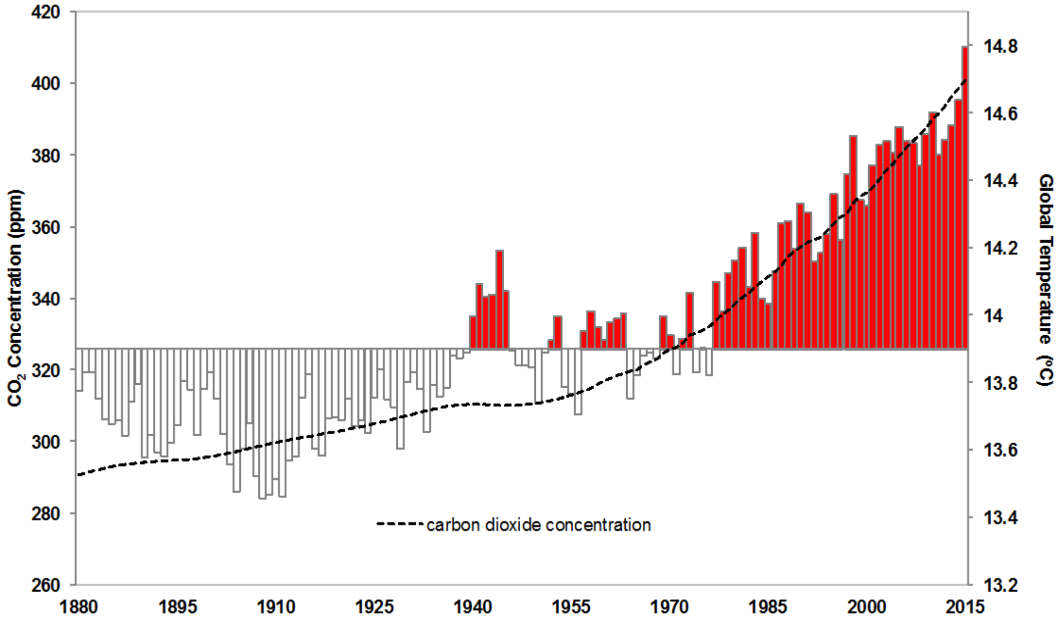
[24] As part of the Scripps CO_2 Program, measurements of atmospheric CO_2 concentration began in 1957 at La Jolla, California and at the South Pole, and in 1958 at Mauna Loa Observatory. These measurements were gradually extended during the 1960's and 1970's to comprise sampling at an array of 10 stations situated along a nearly north-south transect mainly in the Pacific Ocean basin (KEELING *et al*., 2005).

[25] They were started by C. D. Keeling of the Scripps Institution of Oceanography in March of 1958 at a facility of the National Oceanic and Atmospheric Administration (NOAA) and since May of 1974, NOAA runs its own measurements in parallel with those made by the Scripps team, led by R. Keeling, son of the former Keeling.



Notes: CO_2 concentration data are expressed in dry mole fraction expressed in parts per million (ppm) and defined as the number of molecules of carbon dioxide divided by the number of all molecules in the air including CO_2 itself, after water vapor has been removed. Red bars indicate temperatures above and white bars indicate temperatures below the global mean temperature over land and ocean, combined for the base period 1901 to 2000 (the twentieth century average) of 13.9 °C. Anomalies more accurately describe climate variability or larger areas than absolute temperatures do, and they give a frame of reference that allows more meaningful comparisons between locations and more accurate calculations of temperature trends (NOAA, 2016c).

Figure 7 - Atmospheric carbon dioxide concentrations (in ppm) and global temperature anomalies (in °C) over the years 1880 to 2015.

Source: Prepared by the author based on data from ETHERIDGE *et al*., (1998) for CO_2 concentrations for 1880 through 1958, NOAA (2016b) for CO_2 concentrations from 1959 to 2015, and NOAA (2016b) for the temperature anomalies.

Given the historical evidence, the IPCC AR5 WGI report (IPCC, 2013a) indicated that the total net cumulative emissions of anthropogenic CO_2 is the main driver of long-term warming since pre-industrial times. Furthermore, the warming trend in global average temperatures is expected to continue throughout the twenty-first century. Increases in global surface temperatures are projected to range between 0.4 °C and 2.6 °C by mid-century (averaged in the period 2046-2065), and between 0.3 °C and 4.8 °C by late century (2081-2100) relative to pre-industrial values (1850-1900), with a likely increase in excess of 1.5 °C for all pathways of GHG emissions and atmospheric concentrations considered, [26] except the one representing the most stringent mitigation

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[26] The IPCC uses four GHG concentration trajectories called Representative Concentration Pathways (RCPs) RCP 2.6, RCP 4.5, RCP 6, and RCP 8.5, are named after a possible range of radiative forcing

scenario, which assumes that annual GHG emissions peak between 2010 and 2020, declining substantially thereafter (IPCC, 2013b).

Warming on this unprecedented scale is very likely to cause massive adverse impacts on ecosystems and human development, due to increased risk of droughts, sea-level rise, higher incidence of extreme weather events, ocean acidification, and an increased likelihood of many vector-borne diseases in new areas. SOLOMON *et al.* (2009) remarks that, because of the longevity of the atmospheric CO_2 perturbation and ocean warming, irreversible climate changes due to past CO_2 emissions have already taken place, and future CO_2 emissions would imply further irreversible effects on the planet. If the current warming trend is not broken, there will be dramatic negative effects on global ecosystems as well as on the global economy. The IPCC has identified the following risks that span sectors and regions with high confidence level (IPCC, 2014b):

i. Death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise.
ii. Severe health issues and disrupted livelihoods for large urban populations due to inland flooding in some regions.
iii. Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services.
iv. Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas.
v. Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings.

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values in the year 2100 relative to pre-industrial values (2.6, 4.5, 6.0, and 8.5 W/m^2, respectively). These trajectories are consistent with a wide range of possible changes in future anthropogenic GHG emissions. RCP 2.6 includes the most stringent mitigation scenario, which aims to keep global warming likely below the 2 ºC target (IPCC, 2014a).

vi. Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions.

vii. Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic.

viii. Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods.

These risks represent particular challenges to least developed countries and vulnerable communities in view of their limited ability and resources to cope (IPCC, 2014b; HANSEN AND SATO, 2016). Other studies suggest that the impacts of unabated climate change may be even more dramatic than those estimated by the IPCC (e.g. OECD, 2012).

The growing scientific evidence has allowed for a global consensus to be reached that climate change represents a serious potential threat to the world's wellbeing and for a mobilization towards a global response to climate change to be initiated. Such that in 1990, an intergovernmental negotiating process was established under the auspices of the UN General Assembly, the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), for the preparation of a Framework Convention on Climate Change (FCCC), containing appropriate commitments, and any related instruments, taking into account proposals that may be submitted by countries participating in the negotiating process, the work of the IPCC and the results achieved at relevant international meetings (UNGA, 1990).

The United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1992 and entered into force in 1994 with over 150 signatories (Parties) (UNFCCC, 2016a). Its ultimate objective consists in achieving stabilization of GHG concentrations in the atmosphere at a low enough level to "prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992). However, it does not specify what atmospheric concentration level that would be, nor how to assess what is “dangerous” (KNUTTI *et al.*, 2015).

In 1995, the Parties to the Convention launched discussions and negotiations on how the objective of the Convention could be met in their first annual Conference of the Parties (COP) held in Berlin, and, in 1997, adopted the Kyoto Protocol (UNFCCC, 2016b). The Kyoto Protocol aimed to reduce GHG emissions by requiring each of the participating developed countries - Annex I Parties - to make quantified emissions reductions relative to their 1990 emissions levels, on the basis of “common but differentiated responsibilities”, to be achieved over the first commitment period, from 2008 to 2012 (UNFCCC, 2016b). The combined commitments totaled in average a five percent reduction against 1990 emissions levels. Further commitments to reduce GHG emissions by at least 18 percent below 1990 levels would take place during a second commitment period, from 2013 to 2020; however, it did not achieve sufficient ratification by member Parties.

Even though, according to recent analysis by SHISHLOV *et al.* (2016), all countries with commitments under the first commitment period of the Kyoto Protocol have fully complied, the treaty is deemed to have failed to induce sufficient emissions reductions and to provide an effective solution to the climate stabilization challenge (LONG, 2015). In fact, because the Kyoto Protocol did not address emissions from developing countries and the United States did not ratify it, many large GHG emitters were not covered. The reduced support and engagement of the international community and the subsequent inability to produce its successor led to the pursuit of a different approach to the global climate change debate, aiming for a more inclusive and flexible plan that would push climate action forward as rapidly as possible (UNFCCC, 2016b).

While the international climate negotiations were being revamped, the scientific community was positing that limiting global average temperature increase at around 2 ^{o}C above pre-industrial levels or even lower would probably be required to avoid irreversible, catastrophic climate change (GRAßL *et al.*, 2003; HANSEN 2005; HANSEN *et al.*, 2008; ROCKSTRÖM *et al.*, 2009). At the 2010 Cancun Climate Conference, the climate stabilization objective was specified as limiting global average temperature increase to below 2 ^{o}C above pre-industrial levels by the end of the century (UNFCCC, 2010). In 2011, it was further recognized that urgent action was needed so as to achieve the so-called “2 ºC target” (UNFCCC, 2012).

In 2015, a new international agreement to combat climate change was adopted, the Paris Agreement, in which the climate stabilization target was revised to well below 2 ºC above pre-industrial levels and all 197 signatories and Parties to the UNFCCC agreed to pursue further efforts aiming at limiting temperature increase to below 1.5 ºC (UNFCCC, 2015).[27] Although all signatories committed to establishing and reporting on nationally determined emission reduction measures and targets, none of them is legally bound to any specified emissions reduction target.

2.3.2. Carbon budgets and emissions pathways associated with the “2 ºC target”

In order to limit the temperature increase caused by anthropogenic CO_2 emissions to a prescribed temperature threshold, cumulative anthropogenic CO_2 emissions need to be capped to a specific amount, typically referred to as a carbon budget or quota (ROGELJ *et al.*, 2016a).[28] Global temperature increase targets are converted to carbon emission targets with the help of carbon-cycle climate models that simulate the complex exchange processes between atmospheric CO_2 and different carbon reservoirs, discussed above in section 2.3.1, and reveal that eventual warming and, consequently climate change, is accurately proportional to cumulative carbon emissions (MATTHEWS *et al.* 2009; MEINSHAUSEN *et al.*, 2009). However, this near-linearity does not hold for other non-CO_2 GHGs.

For a 66 percent probability of staying below the prescribed 2 ºC target, the IPCC AR5 WGI indicates a maximum CO_2 emissions budget of 2,900 gigatons (Gt) CO_2eq, of which an estimated 1,890 Gt would have already been emitted by 2011, leaving roughly 1,000 GtCO_2eq to be emitted thereafter (IPCC, 2013b; KNUTTI AND ROGELJ, 2015). These values already account for non-CO_2 forcings (IPCC, 2013b). A lower warming target, or a higher likelihood of remaining below the 2 ºC target, would require lower cumulative CO_2 emissions, as shown in Figure 8.

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[27] The Paris Agreement entered into force in November 2016 and has been ratified by more than one hundred and twenty Parties as of December 2016 (UNFCCC, 2016c).

[28] In this study, the term ‘carbon budget’ will be used.

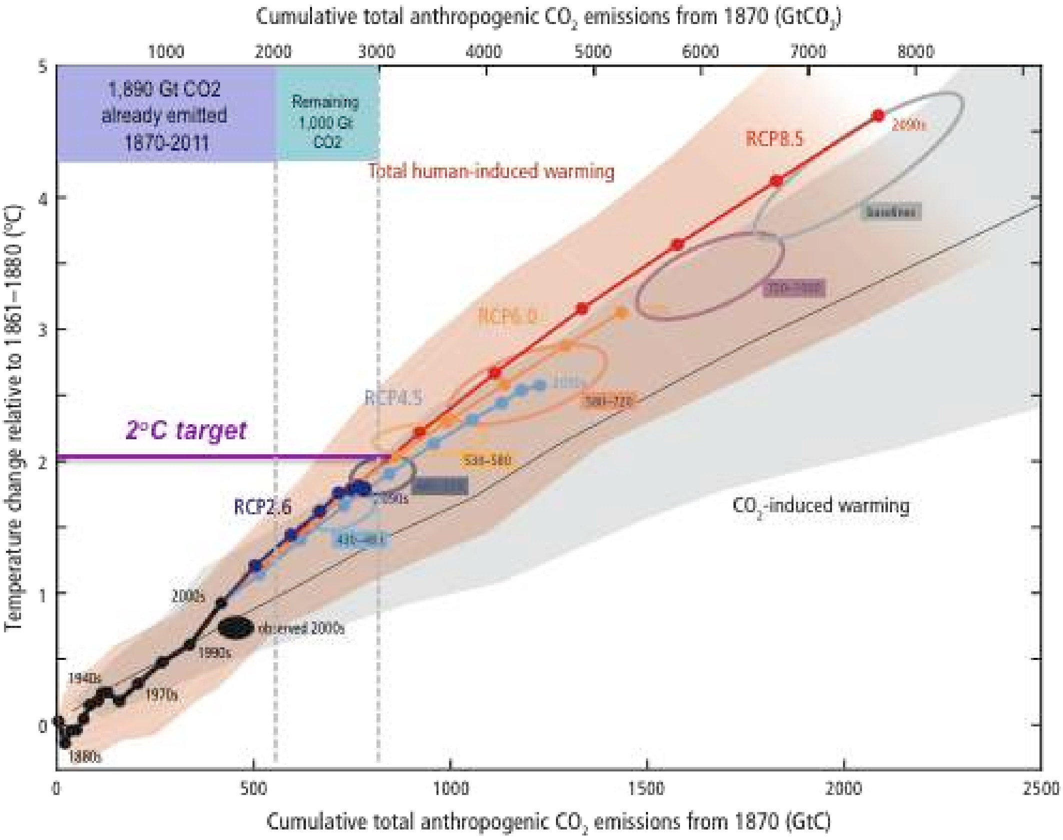

Figure 8 - Simulated global mean surface temperature increase as a function of cumulative total global CO$_2$ emissions and cumulative emissions budget associated with the 2 °C target.

Source: Adapted from figure SPM.10 in IPCC (2013b).

Note: It was derived from various lines of evidence. Model results over the historical period (1860–2010) are indicated in black. The colored plume illustrates the multi-model spread over the four RCP scenarios. Dots indicate decadal averages, with selected decades labeled. Ellipses show total anthropogenic warming in 2100 versus cumulative CO$_2$ emissions from 1870 to 2100 from a simple climate model (median climate response) under the scenario categories used in IPCC's Working Group III (WGIII). Temperature values are given relative to the 1861–1880 base period, and emissions are cumulative since 1870.

The carbon budget above represents just one of several budgets associated with the 2 °C target published in the IPCC AR5 and recent literature. ROGELJ *et al*. (2016b) have identified the different budgets available and provide an overview of how they are defined and calculated. They have identified three different approaches to carbon budget: budget for CO$_2$-induced warming, "threshold exceedance budget" (TEB), and "threshold avoidance budget" (TAB). The first approach is deemed by the authors the most scientifically robust, however it is also the least practical in the real world. TEBs allow for the assessment of non-CO_2 forcing influence on the size of carbon budgets but are derived from scenarios that fail in limiting warming to the prescribed target. Finally, TABs would be preferred because not only they allow for the assessment of non-CO_2 forcing influence on the size of carbon budgets but can be derived from scenarios that are more compatible with climate stabilization targets. The TEB approach was used by IPCC AR5 WGI to calculate carbon budgets that account for non-CO_2 forcing, such as the one described above and depicted in Figure 8.

Regardless of the approach taken, all carbon budgets associated with the 2 ^{o}C target imply stringent emission reductions over the next decades and net zero CO_2 emissions in the medium to long term (ROGELJ *et al.*, 2015 and 2016b). In fact, it may be necessary to deploy mitigation strategies that go beyond carbon neutral emissions. Negative emission strategies, such as large-scale removal and sequestration of CO_2 from the atmosphere, have been pointed by several studies as a critical alternative (AZAR *et al.*, 2006; AZAR *et al.*, 2010; ZEP AND EBTP, 2012; KRIEGLER *et al.*, 2013; TAVONI AND SOCOLOW, 2013; CLARKE *et al.*, 2014; OECD/IEA, 2016b).[29] There is a range of negative emissions technologies at various stages of development under consideration worldwide, including afforestation and reforestation, capturing CO_2 directly from the air by engineered chemical reactions (DAC), enhanced weathering of minerals (EW), and the combination of biomass conversion to energy products (electricity, heat, and fuels) and carbon capture and storage (BECCS), [30] [31] as presented in MCGLASHAN *et al.* (2010) and SMITH *et al.* (2016).

Similarly, there are many different emissions pathways and timing associated with meeting the 2 ^{o}C target (CLARKE *et al.*, 2014; KRIEGLER *et al.* 2014b).[32] Regional contributions to the necessary overall mitigation would vary significantly

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[29] So-called negative emissions technologies are those that result in the net removal of greenhouse gases from the atmosphere (SMITH *et al.*, 2016).

[30] Other abbreviations can be found in the literature, including "BECS", "biomass-based CCS", "BCCS", "biotic CCS" (KARLSSON AND BYSTRÖM, 2011), and Bio-CCS (AZUR, 2010; ZEP AND EBTP, 2012). In this study, the abbreviation BECCS will be used.

[31] BECCS permanently removes from the atmosphere the CO_2 absorbed by the biomass, yielding “negative emissions”. CO_2 is absorbed during biomass growth and then captured, instead of being released back into the atmosphere when combusted for energy production.

[32] Emissions profiles in the existing modeling literature are determined by three interrelated factors: (1) the degree of overshoot, (2) technology options and associated deployment decisions, and (3) policy assumptions (CLARKE *et al.*, 2014).

depending on relative baseline emissions, mitigation potentials, terms of trade, and extent of international effort-sharing (CLARKE *et al.*, 2014; KRIEGLER *et al.* 2014b). Based on over eighty idealized implementation scenarios in IPCC's AR5 Scenario Database and assuming default technology cases,[33] Asian countries together would be by far the highest contributors, with a median level above 600 $GtCO_2eq$, followed by OECD 90 countries with approximately 400 $GtCO_2eq$, countries of the Middle East and Africa with less than 200 $GtCO_2eq$, countries from the Reforming Economies of Eastern Europe and the Former Soviet Union with around 150 $GtCO_2eq$, and countries of Latin America and the Caribbean with less than 100 $GtCO_2eq$ (CLARKE *et al.*, 2014).

How fast or slow carbon budgets would be consumed would also vary, depending inter alia on the levels of stringency of fragmented climate policy action. Recent studies using several Integrated Assessment Models (IAMs)[34] and emissions and socio-economic scenarios based on cost-effective pathways that deliver a medium (50-66 percent) chance of meeting the 2 °C target indicate median levels of global emissions of 34 to 47 $GtCO_2eq$ in 2030 and 17 to 35 $GtCO_2eq$ in 2050 (KRIEGLER *et al.*, 2013; AVERCHENKOVA *et al.*, 2014; DESSENS *et al.*, 2014; KRIEGLER *et al.*, 2014b; UNEP, 2015). The low climate impact scenarios and the implications of required tight emission control strategies project, known as the LIMITS project, is one of these studies that exploit the potential range of 2 °C emissions pathways (KRIEGLER *et al.*, 2013). They consider two different long term forcing targets associated with high (66 percent) and even (50 percent) chances of meeting the 2 °C target, i.e. reaching atmospheric greenhouse gas (GHG) concentrations at roughly 450 and 500 ppm CO_2eq in 2100, respectively, and different timeframes (e.g. immediate, starting in 2020, starting in 2030) and levels (lenient and stringent) of mitigation efforts. Their findings indicate that by delaying action until 2030 global emissions would increase to as much as 65 $GtCO_2eq$ in 2030, thus, significantly reducing the chances of meeting the 2 °C target (to as low as 39 percent).

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[33] The AR5 Scenario Database (IAMC AR5 Scenario Database, 2014) comprises 31 models and 1,184 scenarios (KREY *et al.*, 2014).

[34] In climate change assessment, IAM refers to a mathematical tool that considers the social and economic factors that drive GHG emissions, the biogeochemical cycles and atmospheric chemistry that determines the fate of those emissions, and the resultant effect on climate, ecosystems and human welfare (DESSENS *et al.*, 2014).

In preparation to the Paris Agreement, by December 2015, one hundred and eighty seven countries that accounted for over 96 percent of global CO_2 equivalent emissions in 2012 had submitted climate pledges (so-called "Intended Nationally Determined Contributions" [INDCs]) outlining carbon reduction targets based on post-2020 action (KNUTTI *et al*., 2016; ROGELJ *et al*., 2016a). However, according to recent studies (OECD/IEA, 2015a; UNEP, 2015; ROGELJ *et al*., 2016a), in the absence of additional emission reduction efforts, the estimated carbon budgets associated with the 2 ^oC target could be consumed as soon as 2030, and emissions would equate to scenarios that limit global average temperature increase in excess of the intended 2 ^oC target (median of 3.2 ^oC at a 66 percent chance) (ROGELJ *et al*., 2016a).

2.3.3. Carbon impact of energy use

The primary driver of human-induced climate change has been and continues to be the combustion of fossil fuels for energy production and use (BLANCO *et al*., 2014), as carbon dioxide resulting from the oxidation of carbon in fuels during combustion is the largest component of anthropogenic GHG emissions.

CO_2 emissions from fossil fuel combustion and industrial processes correspond to almost 70 percent of the total cumulative anthropogenic emissions from 1750 to 2011, and have increased consistently in recent decades, having more than tripled from 420 to 1,300 $GtCO_2$ between 1970 and 2010, thereby contributing with almost 80 percent of the global carbon emissions increase in that period (IPCC, 2014a). Today, fossil fuels meet more than 80 percent of total primary energy demand and account for over 90 percent of energy-related emissions (OECD/IEA, 2015b). This explains why energy consumption continues to be the most important source of anthropogenic carbon emissions and, thus human induced climate change.

Global primary energy supply increased by almost 150 percent between 1971 and 2013, mainly relying on fossil fuels (OECD/IEA, 2015b). In fact, use of coal has increased since 2000 and, as a result, reversed the slight decarbonisation trend. In 2013, global CO_2 emissions from fossil fuel combustion reached 32.2 $GtCO_2$, an increase of 2.2 percent over 2012 levels, which was primarily driven by increased consumption of coal in developing countries (OECD/IEA, 2015b). However, they stayed flat in 2014 despite an increase of around 3 percent in the global economy marking the first time in at least 40 years that a halt or reduction in emissions has not been tied to an economic crisis (IEA, 2015a).

Whether this stabilization will be maintained or even mark a sharper decoupling from economic growth remains to be seen. Part of the reduction seen in the European Union in 2014 was due to a mild winter, which significantly reduced CO_2 emissions related to heating, and increased power generation from non-hydro renewables, as a result of active decarbonisation policies. Moreover, global demand for coal had an unprecedented cut back according to preliminary data, with a slight decrease (-0.9 percent) that sharply contrasts with the average annual growth of 4.2 percent over the last decade (OECD/IEA, 2015d). This is in great part due to ongoing changes in the Chinese economy with slower energy demand growth, less dependency on coal-intensive sectors, and increased policies encouraging the use of alternative fuels (OECD/IEA, 2015d; BP, 2016). As a result of these changes BP's latest energy outlook forecasts an annual growth rate of only 0.5 percent in global coal demand out to 2035.

Despite the forecasted decrease in coal consumption and increase in the use of non-fossil energy sources (such as nuclear and hydropower), fossil fuels are expected to remain the dominant source of energy accounting for 75 percent of total energy supplies in 2030 (OECD/IEA, 2015b). Similarly, despite substantial decline in energy intensity in industrialized countries, primary energy demand is expected to grow at least 20 percent between 2014 and 2030, primarily driven by higher levels of energy consumption needed to bridge the energy divide and by global population growth.

As noted in section 2.2, roughly half of the world's population lives in energy poor countries, where significant improvements in wellbeing are needed. More than one third of the world population has an average primary energy consumption rate equal to or even below 30 GJ, which is roughly one seventh of the average energy use in affluent countries.[35] About 40 percent of the projected increase of 2.4 billion in population by 2050 is expected to take place in the least developed part of the world, which currently endures an average primary energy consumption rate below 15 GJ.

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[35] See footnote 3.

Meeting these energy needs while sharply curbing emissions will require substantially higher energy-demand savings, as well as higher deployment levels of low-carbon technologies such as nuclear, carbon dioxide capture and storage (CCS) and non-hydro renewables, and of carbon dioxide removal (CDR) or negative emissions technologies, such as bio-energy combined with CCS (BECCS), as noted in section 2.3.2. According to recent outlook reports the rate of growth of energy-related carbon emissions could halve by 2030 relative to the past twenty years as a result of faster gains in energy efficiency and a transition to lower-carbon fuels following current policies and recent international pledges (OECD/IEA, 2015d; BP, 2016).

According to studies using IAMs and emissions and socio-economic scenarios based on cost-effective emissions pathways that deliver a medium chance of meeting the 2 ^{o}C target, the use of BECCs or other types of negative emissions technologies in the second half of the 21st century will be critical to compensate for the fact that the majority of the remaining carbon budgets will likely be emitted by mid-century (KRIEGLER *et al.*, 2013; SMITH *et al.*, 2016).

In this context, the carbon emissions associated with the additional energy needed to bridge the energy divide and achieve higher levels of collective wellbeing only add to the already daunting challenge of securing climate stabilization.

2.4. The energy use-human development nexus: a literature overview

2.4.1. Traditional focus on economic growth

Most research efforts related to the relationship between energy use and human development have been mostly driven by concerns associated with potential impacts of energy policies on economic growth. For many years, and in particular after the Great Depression and Second World War, nations have equated development with economic growth and industrialization.

Until the 1970s energy use was overlooked by economic theory and, indeed, historiography in general (CARBONNIER AND GRINEVALD, 2011). Then, with the advent of the oil crisis in the 1970s, rising concerns about costs and resource scarcity brought energy to the forefront of domestic and foreign policies, prompting questions on whether and how energy consumption affected economic growth. Aiming at better guiding policy makers on energy conservation policies and their potential impacts on the economy, many studies started to empirically analyze the relationship between energy and development by testing for causality between energy use and economic growth, typically measured by GDP.

The needed knowledge base started to be built with KRAFT AND KRAFT (1978), followed by a wealth of studies using various econometric approaches (including Granger causality tests, error correction model, cointegration, vector autoregression, and panel data analysis), covering different groups of countries and development stages, as well as, different time periods, spanning from as early as 1947 until 2011, as shown in Appendix A. An overview of these studies reveals that the use of different time span, set of countries, data sources, and econometric methods have resulted in diverse outcomes (CHONTANAWAT *et al.*, 2008; HUANG *et al.*, 2008; OZTURK, 2010; CHEN *et al.*, 2012; MENEGAKI, 2014).

KRAFT AND KRAFT (1978) explored the causal relationship between gross national product and energy consumption using annual data for the United States over the period 1947-1974, and their results suggest that there is a uni-directional causal relationship from economic growth to energy consumption. However, a subsequent research (AKARCA AND LONG, 1979) using the same data over different time periods obtained different results. Estimation methodologies also proved to be a relevant factor in the diverging results found in further studies (AKARCA AND LONG, 1980; YU AND HWANG, 1984; YU AND CHOI, 1985; EROL AND YU, 1987a, 1987b; YU AND JIN, 1992; cited in HUANG *et al.*, 2008).

According to CHONTANAWAT *et al.* (2008), a large number of studies were based upon the ‘Granger-causality’ principle (GRANGER, 1969 and SIMS, 1972). However, the majority covered only data from the United States or, at most, a small group of developed countries between the 1940s and the 1980s. Another group of studies used cointegration and the error correction model (GRANGER, 1988) using also data from some developing countries from the 1950s through the early 2000s. Yet, another set of studies used the HSIAO (1981) technique, which enhances Granger-causality by incorporating the use of AKAIKE (1970) ‘final prediction error’ (FPE) criteria on data from the U.S., Latin America and several Asian countries over the period between 1940s and the early 2000s.

Subsequent studies include multivariate analyzes encompassing other variables besides economic growth and energy consumption, in spite of data limitations. For instance, HALICIOGLU (2009) and ZHANG AND CHENG (2009) included foreign trade and urban population in addition to economic growth and energy consumption in their analyses. More recent multivariate analyses have included CO_2 emissions into their modeling frameworks (SOYTAS *et al.*, 2007; APERGIS AND PAYNE, 2009; SOYTAS AND SARI, 2009; ZHANG AND CHENG, 2009; PAO AND TSAI, 2010; CHANG AND CARBALLO, 2011; AROURI *et al.*, 2012; and OMRI, 2013), primarily because climate change policies commonly entail energy conservation policies, which can potentially impact economic growth. Even though most of these studies concluded that energy consumption is often a key determinant of increased CO_2 emissions, the outcome of their empirical results have also been inconsistent, as shown in Appendix A.

Notwithstanding the inconsistency in findings, the relationship between energy consumption and economic growth has been primarily described as one of the following four competing hypotheses in those studies:

i. The neutrality hypothesis refers to the absence of a causal relationship between energy consumption and economic growth, i.e. the two variables are unrelated. In this case, other factors, besides economic growth, directly or indirectly affect energy consumption, and vice-versa.

ii. The conservation hypothesis refers to a uni-directional causality from economic growth to energy consumption, i.e. economic growth leads to increased energy consumption with no feedback.

iii. The growth hypothesis refers to a uni-directional causality from energy consumption to economic growth, means that energy can be considered as a limiting factor, or essential input, to economic growth.

iv. The feedback hypothesis refers to a bi-directional causality between energy consumption and economic growth, implying that energy consumption and economic growth are jointly determined and affected at the same time.

The policy implications of some of these hypotheses can be significant. Studies that have found the energy-GDP nexus prescribed under the growth hypothesis argue against reductions in energy consumption due to its adverse impact on GDP and support increases in energy consumption as a potential contributor to economic growth. Similarly, in the feedback hypothesis, any restriction on energy use would impede economic growth. In contrast, energy conservation policies would only be encouraged under the neutrality or conservation hypotheses.

CHONTANAWAT *et al.* (2008) conducted a systematic review combining statistical methods and using IEA data on 100 countries over the period from 1965 to 2000 and concluded that causality running from energy consumption to economic growth occurs more often in OECD/developed countries than in non-OCDE/developing ones. Therefore, according to this study, energy conservation policies should not be pursued in OECD/developed countries, as they would likely have an impact on their economic growth.

Meanwhile, another study published one month later (HUANG *et al.*, 2008) presents an analysis with a similar number of countries (eighty-two countries split in four income groups) using panel data from 1972 to 2002, and does not find any evidence indicating that energy consumption leads to economic growth in the high income group (i.e. OECD/developed countries). Hence, HUANG *et al.*, (2008) encourage stronger energy conservation policies in these countries. Notably, according to both studies, energy conservation policies would not have a significant impact on the GDP of the developing world.

CHEN *et al.* (2012) observed that the different results found in the literature may have been caused by factors such as the use of distinct subject selections (including GDP and energy consumption), time spans, econometric approaches and/or other explanatory variable selections. In an attempt to help understand the controversial and inconsistent empirical results found in the literature, they prepared a comprehensive study on this issue based on a detailed literature review using a meta-analysis and a multinomial logit model. They used 174 samples from 39 studies found in the literature that test the relationship between energy consumption and economic growth to help determine how this relationship is affected by those factors. The dependent variables consisted of the four competing hypotheses on the relationship between energy consumption and economic growth. The independent variables included the socio-economic characteristics, research target characteristics and estimation methods.

Their findings suggest that if the data sets cover the period after the year 2000 the growth hypothesis will be the most likely outcome over the other three types. Conversely, there is no predominant hypothesis if the data sets cover the 1960s. Thus, showing that different time periods used in testing the relationship between energy consumption and economic growth affect the empirical results differently. Similarly, the use of the Granger-causality test tends to infer the feedback hypothesis, while the use of other estimation methods tends to imply the neutrality hypothesis. Moreover, data sets comprised of developed countries tend to result in the conservation hypothesis, whereas those comprised of developing countries tend to infer the growth hypothesis. Thus, denoting that different econometric approaches and/or levels of economic development of the countries selected will affect the results differently as well.

Despite the inconclusive results on the direction of econometric causality between energy consumption and economic growth, the scientific community seems to have reached a consensus that energy is a critical factor for economic development (OECD, 2013; FIZAINE AND COURT, 2016).

2.4.2. Recent interest in broader aspects of human development

Concerted international efforts towards global sustainability since the adoption of the Millennium Declaration (UNGA, 2000) by 189 heads of states in 2000 have led research efforts related to energy consumption and economic growth to include broader aspects of human development. PASTERNAK (2000), SMIL (2003), DIAS *et al.* (2006), MARTINEZ AND EBENHACK (2008), JACKSON (2009), STEINBERGER AND ROBERTS (2009, 2010), SMIL (2010b), COSTA *et al.* (2011), MAZUR, (2011), PASTEN AND SANTAMARINA (2012), RAO AND BAER (2012), STEINBERGER *et al*. (2012), JORGENSON (2014), STECKEL *et al*. (2013), UGURSAL (2014), and LAMB AND RAO (2015) all use the Human Development Index (HDI) or its components as proxy measures for human development beyond the economic dimension in their analyse of the link between energy consumption and human development.

HDI is a measure of human development that combines proxies for three important human capabilities: health (represented by life expectancy), education (represented by literacy and school enrollment), and a decent standard of living (represented by GDP per capita).[36] The HDI was introduced by the United Nations Development Programme (UNDP) in 1990 as an alternative to address some of the shortcomings of Gross National Product (GNP) (STANTON, 2007) (see section 3.3.2 below). Among other limitations, GNP was unable to inform on the quality of life of the people. As such, HDI has been consistently used as a reference metric to compare social and economic development within and between countries across time (COSTA *et al.*, 2011). It uses readily accessible source of data across 187 countries and is based on a reasonably consistent basis since 1990 (UNDP, 2013).

Interestingly, most of these studies have found strong correlations between energy consumption and/or CO_2 emissions and HDI levels in developing countries, but a decoupling pattern in industrialized countries, as improvements in quality of life start to level off at a certain saturation level. An important take away from these results is the understanding that while increased energy consumption is bound to increase economic growth, and CO_2 emissions into the atmosphere, it may not necessarily improve human development after societies have reached a certain level of economic development and quality of life, including adequate housing, ample food supply and clean water, decent transportation, and good indicators of health and education.

This saturation or threshold phenomenon is well examined in MAX-NEEF (1995), PASTERNAK (2000), MARTINEZ AND EBENBACK (2008), JACKSON

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[36] The indices are relative and normalized, such that each component is calculated with respect to the minimum value in the sample, and then normalized to the maximum difference found in the sample. A country potentially having the highest score across all three dimensions would have an HDI value of 1.0.

(2009), STEINBERG AND ROBERTS (2009 AND 2010), SMIL, (2010B), MAZUR, (2011), and PÎRLOGEA (2012). It is also depicted in the regression curves in Figure 9 below. For countries with low or medium HDI rankings (developing countries), slight increases in energy consumption and carbon emissions translate into significant improvements in human development; hence a strong, positive, and roughly linear relationship is observed. Meanwhile, for countries with higher HDI rankings (mostly industrialized countries) after a modest threshold is reached, it takes significant increases in energy consumption and carbon emissions to make further improvements in human development, if any.

Moreover, this point of inflection has been equated to a threshold level equivalent to approximately 105 GJ per capita primary energy consumption in PASTERNAK (2000), MARTINEZ AND EBENHACK (2008), and UGURSAL (2014). PASTERNAK (2000) and UGURSAL (2014) have estimated a range from 378 to 492 EJ of overall energy needed to reach such threshold level globally.[37] According to PASTERNAK (2000) this threshold would be achieved in 2020 while, according to UGURSAL (2014), it would be achieved only by 2100. Other ideal levels have been determined based on average GDP per capita, HDI, basic needs access, and life expectancy (COSTA *et al*., 2011; UGURSAL, 2014; and LAMB AND RAO, 2015).

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[37] This range refers to achieving a minimum of 4,000 kWh (or 14.4 GJ) per capita electricity consumption or an estimated (at 7.5 ratio) 108 GJ (or 2580 koe) per capita primary energy consumption.

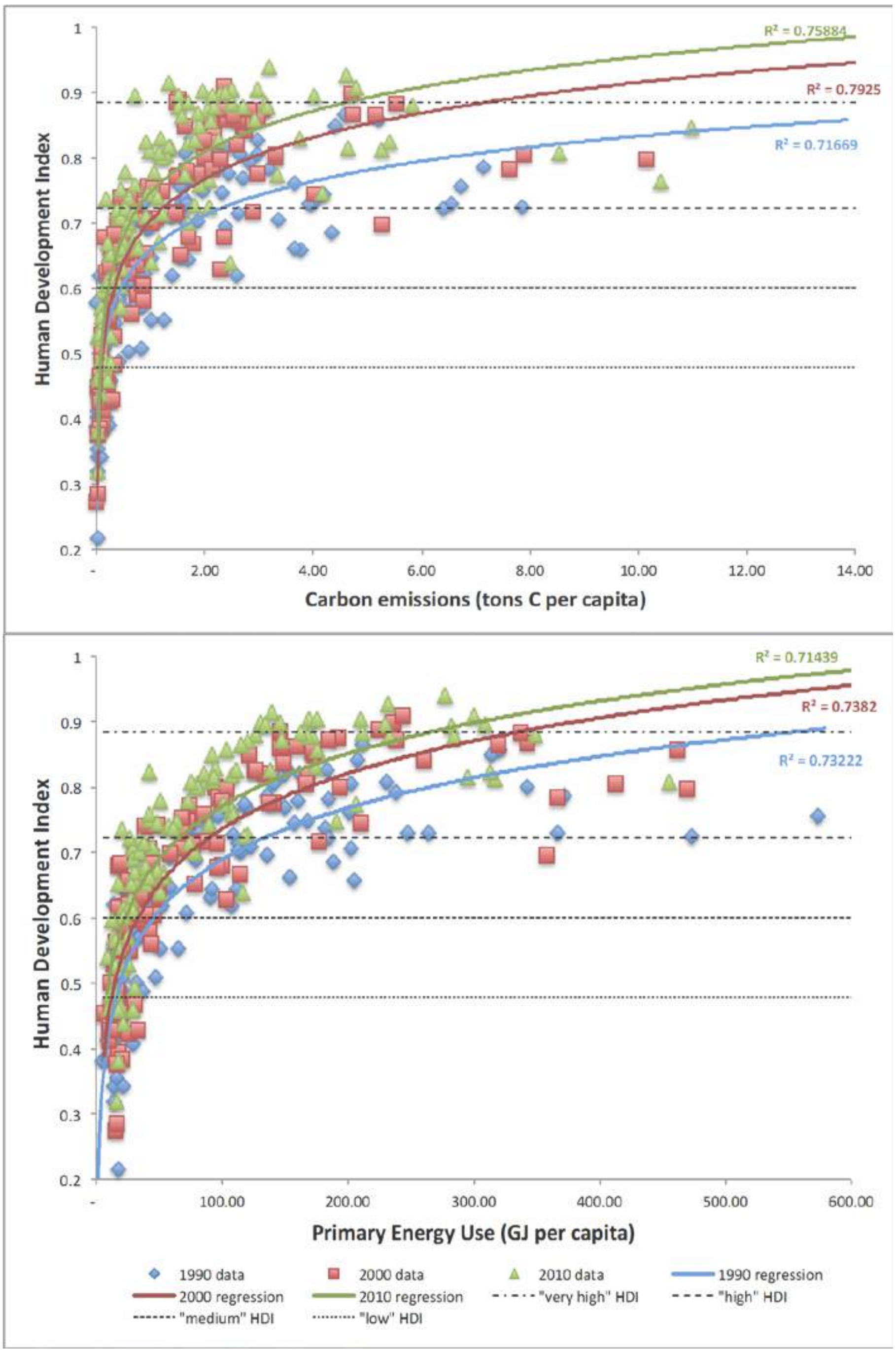

Figure 9 - Saturation and decoupling trend between HDI and carbon emissions (upper plot, 115 countries) and between HDI and energy consumption (114 countries for 1990 data and 116 countries for 2000 data and 2010 data) from 1990 to 2010.

Source: Adapted from STEINBERGER AND ROBERTS, 2010 using data from the World Development Indicators (WORLD BANK, 2016) and the Human Development Report 2013 (UNDP, 2013).

The regression curves in Figure 9 also show that for constant energy consumption and corresponding carbon levels, HDI increased overtime time. For instance, for 2 tons of carbon per capita the expected HDI levels would be 0.712, 0.768, and 0.809 for 1990, 2000, and 2010, respectively. This implies that overall human development has been slowly decoupling from carbon emissions overtime, in other words, becoming somewhat more carbon-efficient as observed in STEINBERGER AND ROBERTS (2009 and 2010) and STEINBERGER *et al*. (2012).

In theory, technological improvements could explain part of this decoupling trend as more energy services are delivered per unit of input energy. However, in practice, the growth of energy efficiency is more than matched by growth in energy consumption as a result of rebound effects, a phenomenon otherwise known as the "Jevon's Paradox" (GREENING *et al*., 2000; AYRES *et al*., 2007; SORRELL, 2007).[38] An example of a rebound effect would be the driver who replaces a car with a fuel-efficient model, only to take advantage of its cheaper running costs to drive further and more often (SORRELL, 2007). DALY (2013) argues that such rebound effects would be avoided if efficiency were to be sought alongside throughput limitation.

STEINBERGER *et al*. (2012) and JORGENSON (2014) further demonstrate that this decoupling is remarkably steady albeit at highly differentiated trajectories when individual countries are taken into account, given their highly differentiated states of carbon emissions and life expectancy. JORGENSON (2014) shows that in some countries the level of anthropogenic carbon emissions per unit of human development (measured in terms of average life expectancy at birth) did not reduce overtime (e.g. Kenya) and has in fact increased during either part of or the whole period between 1970 and 2009 (e.g. China and Australia), which is in part explained by changing effects of per capita GDP on such levels (measured in terms of elasticity coefficients). Another contributing factor is the change in decarbonisation rates (rate at which the carbon emissions associated with each unit of GDP decreases) experienced by each nation, which is in turn driven by changes in the energy intensity of the economy (or energy use per unit of GDP) and changes in the carbon intensity of the energy supply (or carbon emissions per unit of energy).

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[38] The "Jevon's paradox" states that productivity increases, in the end, do not result in resource savings but in accelerated economic growth: "with fixed real energy prices, energy efficiency gains will increase energy consumption above what it would be without these gains" (SAUNDERS, 1992).

However, because they used the HDI or its components as proxy measures for human development or wellbeing, and even though carbon emissions are included in their analyses, current studies on the relationship between energy consumption and human development have yet to encompass the ecological dimension and the intergenerational equity principle, which are critical for achieving sustainable development.

In spite of existing knowledge of the so-called externalities (e.g. MARSHALL, 1890 and PIGOU, 1920), or unintended and uncompensated effects upon others resulting from consumption or production activities as defines in PERMAN *et al.* (2003), there was hope of a limitless, energy-intensive economic development model. Aiming for unending economic growth is not sustainable in a world with environmental limits. In fact, humanity's imprint on the global environment through resource use and waste production may have exceeded the regenerative and absorptive capacity of the biosphere (BARNOSKY *et al.*, 2012; ROCKSTRÖM *et al.*, 2009; STEFFEN *et al.*, 2011), thus compromising the ability of future generations to ensure their wellbeing.

The perception of natural resources and the environment has shifted from a vision of being a limit to economic growth to having an active role in reducing poverty, achieving higher living standards and increasing human development levels. Everything that humanity needs for survival and wellbeing depends, either directly or indirectly, on the natural environment. Humans are part of the natural world and dependent on the use of natural resources to sustain their social and economic wellbeing.

There is evidence that although man-made changes to ecosystems have helped to improve the lives of billions, they are increasing the likelihood of non-linear and potentially abrupt changes in ecosystems (e.g. fisheries collapse, climate change, disease emergence), with important consequences for human wellbeing (HARRIS, 2012). These changes have weakened nature's ability to deliver key ecosystem services such as purification and waste treatment, air quality maintenance, biological control, storm protection, climate regulation, and regulation of human diseases.[39] Data shows,

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[39] For an overview of the condition and trends in the world's ecosystems and services refer to the United

for instance, that progress in HDI has come at the cost of global warming (TOGTOKH, 2011).

In an attempt to better understand the relationship between the pressure placed on the environment and improvements in human wellbeing, several recent studies have begun to explore the different ecological/environmental intensities of wellbeing (EIWB) of countries (DIETZ *et al.*, 2007, 2009, 2012; KNIGHT AND ROSA, 2011; KNIGHT *et al.*, 2013). They define EIWB as the ratio between a measure of stress on the environment, such as the ecological footprint or GHG emissions, and a measure of human wellbeing, typically life expectancy at birth, one of the components of HDI.

As discussed in the following section, the concept of human development has long evolved to incorporate the notion of sustainability setting the stage to a new paradigm of development, which emphasizes the importance of sustaining all forms of resources (e.g. physical, human, financial and environmental) as a precondition for meeting the needs of both current and future generations as well. Under this new development paradigm sustainability is to be achieved by focusing on economic growth, social equity, and environmental protection (WCED, 1987). Interestingly, evidence from STEINBERGER *et al.* (2012) suggests that nations can achieve environmental and social sustainability (in the form of lower carbon emissions and high life expectancy), but only below a given cap of per capita income ($12,000 USD).

While Human Development reports, where the HDI is published annually, discuss the importance of sustainability and the avoidance of environmental degradation and even present various ancillary indicators on the consumption of natural resources, the headline indicator is still the HDI (MORSE, 2003). In order to fully become a measure of sustainable development, the HDI would have to be revised to incorporate resource exploitation and environmental degradation (DESAI, 1995; SAGAR AND NAJAM, 1998; NEYMAYER, 2001; MORSE, 2003).[40] Otherwise, the HDI will continue failing to represent all three dimensions of sustainable development - social,

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Nations 2005 Millennium Ecosystem Assessment, the result of a four-year (2001-2005) study involving more than 1,300 experts worldwide.

[40] Surprisingly, despite the international attention drawn towards sustainable development during the late 1980s and particularly following the Rio Earth Summit in 1992, there have been few calls to ‘green’ the HDI (NEUMAYER, 2001).

economic, and environmental.

To the author’s knowledge there has been no study on the relationship between energy use and human development or wellbeing that uses a measure of the latter that encompasses all three dimensions of sustainable development as a single value, expressed in monetary terms. Possibly, because in order to examine such relationship it is essential to first understand the underlying concepts and dimensions of the new development paradigm, where the goal of economic growth has been replaced by that of human wellbeing, as discussed in greater detail in the next section.

3. Human wellbeing: concepts and measurements from a development perspective

According to the mainstream economic theory, economic growth is the result from the accumulation of factors of production, particularly capital and labor, and from increased productivity (DORNBUSCH *et al.*, 1998). By assuming a high degree of substitutability between factors of production, economic growth is viewed as unlimited (DALY, 2007). In disagreement with this view, ecological economists argue that economic growth reflects the quantitative physical increase in the matter-energy throughput that begins with depletion and ends with pollution (DALY, 2013). As such, economic growth is but a narrow aspect of human development within the energy-development nexus. Human development, in contrast, is associated with the qualitative improvement in the capacity of a given throughput to provide for the maintenance and enjoyment of life in general (DALY, 2013), i.e. human wellbeing.[41]

Human wellbeing from a development perspective has become an important area for policy as it accounts for elements in human life that cannot be defined, explained, or primarily influenced by economic growth (MCALLISTER, 2005). However, as discussed in section 2.4.2 above, it was not until around the year 2000 that studies assessing the relationship between energy consumption and development started to include other variables besides economic growth and use proxy measures for human development beyond the economic dimension. This change can be primarily attributed to growing worldwide concern and interest in sustainability, which is mostly described as the requirement to maintain the capacity to provide non-declining wellbeing over time (NEUMAYER, 2004).

While there has been broad consensus on the need to replace the goal of economic growth with that of human wellbeing as the ultimate purpose of human development, it is not clear what it is or how it should be measured, neither at the individual level or that of a society as a whole (MCGILLIVRAY AND CLARKE,

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[41] Even though the literature often uses the terms ‘‘happiness’’, ‘‘wellbeing’’, ‘‘quality of life”, and “life satisfaction” interchangeably (MCALLISTER, 2005), in this study we refer to ‘‘wellbeing’’ in the context of societal welfare, unless otherwise indicated.

2006; CANOY AND LERAIS, 2007; DODGE *et al*., 2012; KING *et al*., 2014). Human wellbeing cannot be directly observed, making it an ambiguous and abstract concept primarily used to refer to whatever is assessed in an evaluation of a person's situation with focus on the quality of the person's 'being' (GASPER, 2005; MCGILLIVRAY, 2005; MCGILLIVRAY AND CLARKE, 2006). As a result, there is a wide range of conceptual approaches to it in the literature, partly reflecting different contexts, purposes, and areas of concern (see DASGUPTA, 2001; GASPER, 2004; STIGLITZ *et al*., 2009; and ADLER AND SELIGMAN, 2016).

This chapter discusses the challenges associated with trying to define and measure wellbeing from a human development perspective, given its complex and multi-dimensional nature. It shows how even though massive efforts are still needed to arrive at a unified theoretical foundation around human wellbeing, the host of conceptual approaches developed to date have increased awareness and recognition of the combined effects of social equity and environmental protection, alongside economic growth on the achievement of collective wellbeing.

3.1. Early conceptualizations: from material individualism to spiritual collectivism

In order to help better understand the multitude of present-day interpretations of wellbeing, this section renders an overview of dominant conceptual approaches to human wellbeing, which can be traced back as far as ancient Greek philosophical traditions that are founded on distinct views of human nature and of what constitute a good society: *hedonia* and *eudaimonia* (RYAN AND DECI, 2001; MCALLISTER, 2005; RYFF AND SINGER, 2008). The hedonic conception focuses on happiness and self-satisfaction and defines wellbeing in terms of pleasure attainment and pain avoidance. The eudaimonic conception, in turn, focuses on meaning and self-realization and defines wellbeing in terms of actualization of human potentials, i.e. well-considered fulfillment (RYAN AND DECI, 2001). Moreover, in order to make the conceptual analysis more comprehensive, it attempts to make a parallel with other significant conceptualizations present in Eastern philosophical and cultural traditions.

3.1.1. Hedonism: wellbeing as maximization of individual pleasure

Aristippus, a Greek philosopher from the fourth century BCE who founded the Cyrenaic school, believed that the ultimate purpose of human life was to experience as much pleasure as possible while generally avoiding any painful experiences (RYAN AND DECI, 2001). From his perspective, maximizing one's pleasurable moments was the ultimate goal of human life. Wellbeing from a hedonic approach is, therefore, primarily associated with self-satisfaction. Hedonism[42] has been expressed in many forms throughout history, varying from a relatively narrow focus on bodily pleasures to a broad focus on appetites and self-interests, as well as valued outcomes in varied realms (RYAN AND DECI, 2001).

In view of its inconsistencies with military nobility and Christian virtues, hedonism received little attention by scholars and was mostly perceived as a derogatory idea during the Roman Empire and the Middle Ages until Pierre Gassendi (1592–1655), who reinterpreted the concept of pleasure in a distinctly Christian way (MOEN, 2015). Gassendi's work influenced many other Enlightenment thinkers, particularly Thomas Hobbes and John Locke. However, modern history of hedonistic theories is said to start with the work of Jeremy Bentham (MOEN, 2015), considered the founding father of utilitarianism (HIRSCHAUER *et al.*, 2015).

Drawing on the fundamental principles of hedonism, Jeremy Bentham (BENTHAM, 1789) argued that not only human behavior is motivated by pleasure and pain, but their net satisfaction translates into "utility." According to his propositions, society's wellbeing would be the sum of these utilities, such that an ethical course of action was that which led to "the greatest happiness for the greatest number" (STANTON, 2007). Bentham further believed the value of pleasure to be its intensity multiplied by its duration and to not contain any qualitative difference. Later utilitarians, like J. Stuart Mill, argued that there could be qualitative differences, in particular between "higher" and "lower" levels of pleasure (see NUSSBAUM, 2007).

Modern hedonists tended also to think in terms of general good and universal

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[42] The word "hedonism" derives from the Greek word "*hedone*" ("pleasure") (MOEN, 2015).

ends, in contrast to the more egoistic form taken by the ancient Greeks. Henry Sidgwick (1838-1900), in particular, when defining utilitarianism equated it to universalistic hedonism, which directed the individual to act in a way that promoted the happiness of all individuals, as opposed to egoistic hedonism (see SIDGWICK, 1981 [1874], Book IV, Chapter 1, Section 1, p. 200).

Under utilitarianism, or universalistic hedonism, wellbeing was reduced to pleasure and further reduced to the scalar of unitary pleasure or utility (GASPER, 2004), which could in principle be summed across individuals to determine societal wellbeing. However, in the absence of inter-personal comparability, the utility of individuals cannot be aggregated, nor can it be compared in order to consider distribution (STANTON, 2007). Nevertheless, utilitarianism has been the dominant approach to human wellbeing used in mainstream economic theory since the 1930s (STANTON, 2007).

3.1.2. Eudaimonism: wellbeing as the actualization of human potentials

Not in agreement with Aristippus' hedonic approach, Greek philosopher Aristotle (384 to 322 BCE) proclaimed that living a life of contemplation and virtue, in accordance with one’s inherent truth was the pathway to true happiness and wellbeing (NORTON, 1976; cited in RYFF AND SINGER, 2008). Accordingly, *eudaimonia*[43] was “activity expressing virtue” and all that human desires and actions aimed to achieve, and that it was something generated by our actions and not our belongings (STANTON, 2007). Aristotle did not denigrate hedonic pleasure per se, but rather, the pursuit of hedonic pleasure purely for pleasure’s sake (WATERMAN, 2008). Given that such behavior would be contrary to his interpretation of virtue, i.e. a state of character concerned with finding the middle ground between excess and deficiency (RYFF AND SINGER, 2008).

In one of his most influential works, the *Nicomachean Ethics* (ARISTOTLE, 1985 [350 BCE]), while seeking to answer what would be the ultimate purpose of

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[43] The term "*eudaimonia*" is a classical Greek word, consisting of "*eu*" ("good") and "*daimōn*" ("spirit"). It is traditionally translated as happiness but many philosophers, religious masters, and visionaries have denigrated happiness per se as a principal criterion of wellbeing (RYAN AND DECI, 2001).

human existence, Aristotle presented a theory of wellbeing that is still relevant today. According to him, wellbeing consisted in achieving, through the course of a whole lifetime, the best that is within us, i.e. all the goods that lead to the perfection of human nature and to the enrichment of human life. Aristotle was clearly not concerned with the subjective states of wellbeing. Rather, his conception of the highest good towards which we all should be reaching was the task of self-realization, played out individually, each according to his or her own disposition and talent (RYFF AND SINGER, 2008).

According to eudaimonism, individuals have the responsibility to recognize and live in accordance with one's true self (*daimōn*) (BANAVATHY AND CHOUDRY, 2014). The *daimōns* refer to the potentialities of each person, the realization of which represents the greatest fulfillment. Eudaimonic advocates argued that living a life of virtue, and actualizing one's inherent potentials was the way to wellbeing. *Eudaimonia*, thus, incorporates the essence of the two great Greek imperatives: first, to ‘‘know thyself’’ (a phrase inscribed on the temple of Apollo at Delphi), and second, to ‘‘choose yourself’’ or ‘‘become what you are’’ (NORTON, 1976; cited in RYFF AND SINGER, 2008).

Eudaimonic theorists cautioned that not all sources of pleasure foster wellbeing. Instead, they argued that it is the realization of human potential, rather than simply life-satisfaction, that is central to wellbeing (RYAN AND DECI, 2001; MCALLISTER, 2005). In this sense wellbeing cannot be equated merely to a sensation of happiness. Human beings have more faculties than just feeling happiness, pleasure or pain, notably they are creatures of reasoning and of meaning-making, of imagination, and of intra- and inter-societal links and identities (GASPER, 2004).

3.1.3. Eastern conceptualizations: wellbeing through self-transcendence

Questions regarding the essential qualities of a good society and the good life have also captured the minds of great thinkers across Eastern traditions (RYFF AND SINGER, 2008; BANAVATHY AND CHOUDRY, 2014; JOSHANLOO, 2014). The conceptual approaches to wellbeing in Eastern philosophies can also be traced back to ancient times, to the age of Confucius (c. 551 to 472 BCE) in China (ZHANG AND VEENHOVEN, 2008) and to the Vedic and Upanishadic periods (c. 3000 to 1000 BCE) in India (SALAGAME, 2003; BANAVATHY AND CHOUDRY, 2014). As discussed below, except for India’s school of materialist philosophy, eastern conceptualizations of wellbeing are more consistent with the eudaimonic perspective of western theorists. In fact, they go beyond the proposition of the latter, suggesting that collective wellbeing can only be achieved by de-emphasizing individualistic virtues and, ultimately, by cultivating spirituality and self-transcendence.

Confucianism is believed to be at the root of the traditional schools of thoughts in eastern traditions (JOSHANLOO, 2014). Similar to the Greek *eudaimonia*, this ancient philosophy associates wellbeing with achieving a good life, one of virtue, honor, and purpose. Confucius was not so much concerned with the individual wellbeing but how we relate collectively to each other in all contexts. The pivotal idea of Confucianism is ‘Jen’, a feeling of compassion, i.e. concern for the wellbeing of others (ZHANG AND VEENHOVEN, 2008).

The other two major Chinese traditions, Taoism and Buddhism, differed in how they valued life (ZHANG AND VEENHOVEN, 2008), however, they were also wary of bodily pleasures, and promoted instead desire control techniques to keep individuals from pursuing pleasures at the expense of ignoring main virtues (IP, 2011; JOSHANLOO, 2014). Moreover, suffering and negative emotions not only are not considered entirely bad in these cultures, but are thought to contribute to spiritual development.

Indian traditions, in turn, convey three general perspectives on wellbeing: the hedonistic perspective, the transcendent perspective, and the collectivistic perspective (SALAGAME, 2003). These can be associated with the perception of human evolution through a progressive expansion of consciousness as different layers (sheaths) that represent dimensions of awareness which unfold towards a state of realization of one’s transcendent Self (*Ātman*), i.e. true wellbeing (*swasthya*) and welfare (*kalyana*). As such, human beings are believed to transition out of the hedonistic approach to wellbeing through degrees of the collectivistic approach towards the transcendent approach to it as they climb up the evolutionary ladder.

Under the hedonistic perspective, fulfillment of desires, particularly of sensory nature, is the sole criterion towards securing wellbeing. This approach was followed by India's school of materialist philosophy, originally called *Lokāyata* ("prevalent in the world", Sanskrit *lokeṣu āyatam*, "widespread among the people") (BHATTACHARYA, 2009), which was founded around the same time that materialism developed independently in ancient Greece or perhaps slightly before (WOJCIEHOWSKI, 2015).

According to this school of thought, pleasure was asserted as the highest good, and the only reasonable way to enjoy one's life. It rejected the notion of God, dharma (values), law of karma (theory of action leading to rebirth), objective ethical laws, and many other ideas associated with the Vedas (the orthodox traditional wisdom of India) and the spiritualistic schools of Eastern philosophy (e.g. Jainism, Buddhism, Hinduism). Likely this was one of the main reasons it never gained prominence in Eastern philosophies and cultures, although SALAGAME (2003) argues that it is taking hold of the Indian psyche in contemporary times due to westernization and globalization. Another reason lies on the fact that the hedonistic conceptualization not only promotes the pursuit of pleasures at the expense of ignoring main virtues, the cornerstone of achieving the highest good in Eastern cultures, but also the cultivation of self-centeredness, which does not accord with the core values and ethos of collectivistic societies (JOSHANLOO, 2014).[44] While the Vedic tradition does not indorse the hedonistic approach to wellbeing, it does not negate the role and necessity of this aspect of pleasurable experience or materialistic happiness (*viṣayānanda*) (BANAVATHY AND CHOUDRY, 2014).

Lying on the opposite side of the spectrum, the second perspective on wellbeing, upheld by most traditional Indian philosophers, is rooted in the transcendental view of reality, according to which the ideal wellbeing is understood as the realization of one's transcendent Self (*Ātman*) (SALAGAME, 2003). Transcendental happiness (*Brahmānanda*) is regarded as the highest form of happiness that a person can experience. It is transcendental in the sense that it transcends the limitations of compartmentalized individual existence (BANAVATHY AND CHOUDRY, 2014).

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[44] Wellbeing conceptualizations are to a great extent associated with the way the 'self' is perceived. A conspicuous difference between western and eastern traditions lies on the fact that the former define the 'self' primarily based on the ideals of individualism, while the latter tend to regard it as a part of the collective (JOSHANLOO, 2014).

Similar to the eudaimonic perspective in western traditions, it fosters the realization of one's inherent potentials as the way towards securing wellbeing.

However, self-realization is qualitatively different from the self-actualization advocated by eudaimonic theorists (BANAVATHY AND CHOUDRY, 2014). Also contrary to the views of eudaimonic theorists, the transcendent perspective advocates that one does not need to interact with any external object, situation or person in order to fulfill his or her potentials (BANAVATHY AND CHOUDRY, 2014). It starts from the presumption that human beings have intrinsic happiness and contentment within them, waiting to be discovered. Moreover, it is based on an all-encompassing universal vision that aspires for the wellbeing of everyone (SALAGAME, 2003). The causes, determinants and correlates of this kind of conceptualization cannot be equated with any western conceptualization (BANAVATHY AND CHOUDRY, 2014).

The third and last Indian perspective on wellbeing, the collectivistic one, lies in between the two perspectives described above. Similar to *eudaimonia*, it refers to an aspect of happiness derived from the actualization of one's best potentials (*kāvyānanda*) (BANAVATHY AND CHOUDRY, 2014). It acknowledges the numerous differences in the needs and aspirations of people, and the fact that the majority of people have an intermediary approach to life between a purely hedonistic approach and a more spiritual one (SALAGAME, 2003).

3.2. Modern conceptualizations: from economic growth to sustainability

Interest in the wellbeing of people and nations has been central to economists from the founders of modern economics (e.g. Adam Smith, David Ricardo, John Stuart Mill, and Karl Marx) to contemporary economists, such as Paul Streeten, Amartya Sen, Martin Ravallion and Ravi Kanbur (SUMNER, 2004), who have broken away from the utilitarian concept, while viewing wellbeing as a multi-dimensional construct.[45] It is noteworthy, however, that by the end of the 20th century, despite 'rigorous and elegant

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[45] Despite the differences between the hedonistic and eudaimonic approaches, most researchers now believe that wellbeing is a multi-dimensional construct (e.g. DIENER, 2009; STIGLITZ *et al*., 2009; cited in DODGE *et al*., 2012) and that the two approaches to the study of wellbeing are not mutually contradictory (KASHDAN *et al*., 2008).

in its logic', mainstream economics was still uncertain about the implications of policies on human wellbeing (ACKERMAN *et al*., 1997).

As the 21st century unfolds, this shortcoming may be addressed as a result of the process of transformation that economics is believed to be undergoing driven by the mainstream research frontier (COLANDER *et al*., 2004; COYLE, 2007; DAVIS, 2008), which has been making important departures from the key tenets of the standard neoclassical approach (e.g. rationality, selfishness, equilibrium) towards a 'more eclectic position of purposeful behavior, enlightened self-interest and sustainability' (COLANDER *et al*., 2004).

STANTON (2007) provides a detailed account of the evolution of the approaches to wellbeing conceptualizations from the early intellectual history of welfare economics and following this field through three successive revolutions in thought culminating in the theory of human development. SUMNER (2004) also discusses the historical evolution of the debates around the meaning of wellbeing from a human development perspective, focusing on the post Second World War era, when development studies flourished and development economics emerged into a separate discipline within economics. Drawing on the work of these two authors, the following section presents a quick overview of the evolution of modern wellbeing conceptualizations from the birth of welfarism through Sen's remarkable capabilities approach to the most recent conceptual frameworks around the linkages among ecosystem services and human wellbeing, depicting a transition towards more complex and multi-dimensional interpretations of wellbeing that encompass many different aspects of human life.

3.2.1. The predominant one-dimensional conceptualization centered on economic growth

Modern conceptualizations of wellbeing from a human development perspective have largely emphasized the utilitarian approach discussed in section 2.1.1 above. The Marginal revolution of the 1870s saw the concept of marginal subjective utility as the key factor in determining the value of goods in contrast to the classical cost (and labor) theory of value.

The Marginalist Welfare School, the most direct antecedents of today's neo-classical economists, preserved the basic principles of utilitarianism, or universalistic hedonism (STANTON, 2007). This school maintained that there were both material and non-material aspects to wellbeing, whereby the former was the object of focus in the field of economics (ACKERMAN *et al*., 1997). Following the assumption that utility can be expressed cardinally, marginalists used money as a "measuring stick", which became the accepted metric for wellbeing as measurement became increasingly central to economics.

The utilitarian definition of collective wellbeing, as the sum of individual wellbeing, was gradually replaced in normative welfare economics by the idea of "Pareto optimality" (a situation in which no one can be made better off without making someone else worse off). In Pareto optimality, even though individual wellbeing was still seen as utility, collective wellbeing was evaluated on the basis of the presence or absence of Pareto optimality (STANTON, 2007). This conceptual approach was somewhat disregarded in applied neo-classical welfare economics through the use of cost-benefit analysis (CBA) (STANTON, 2007) in public decision-making.[46] The cost-benefit principle runs counter to Pareto optimality since a change that improves the wellbeing of some while diminishing that of others still somehow qualifies as collective wellbeing improvement on the basis of a net benefit. However, this conceptual gap was addressed with the Kaldor-Hicks compensation criterion, which states that a change in the economy can constitute an improvement in collective wellbeing if those who benefit from it gain enough that they can compensate those who are hurt, and still be left with some 'net gain' (COHEN, 2001). As such, it implicitly assumes that the marginal utility of money is the same for all the individuals, in other words, that income distribution is equal.

Pareto optimality combined with the compensation criterion (i.e. the adapted concept of Pareto improvements) led to the use of income as a measure of wellbeing and development (STANTON, 2007). This reflects the direct conflation of economic growth with human wellbeing and development that prevailed particularly in the

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[46] This tool started to be used more extensively after the Second World War when there was a need to ensure that public funds were efficiently utilized (ATKINSON AND MOURATO, 2005).

aftermath of the Second World War, when the economics of development was targeting reconstruction and capital accumulation. At the time, it was assumed that economic growth would "trickle-down" and spread its benefits across society, eventually reducing any poverty (SUMNER, 2004; STANTON, 2007), and thereby improving collective wellbeing. This assumption was supported by the convergence hypothesis associated with the Robert Solow's growth model (SOLOW, 1956), according to which, poor countries end up catching up with richer countries in the long-run as per capita growth rate tends to be inversely related to the starting level of output or income per person (BARRO AND SALA-I-MARTIN, 1992). The fact that poor countries have less capital stocks to start with, each additional unit of capital will have a higher return than in a rich country, following the premise of diminishing returns to capital.[47] [48]

The focus on economic growth intensified during the decades that followed the end of the war (STREETEN, 1981; OECD, 2013). Much of the post-war literature equated development with economic growth and debated how and in what ways growth could be promoted (OECD, 2013). Even though, W. Arthur Lewis, one of the founders of modern development thinking, emphasized already in 1955 that economic growth should not be seen and treated as an end in itself, rather as a means to increase the choices available to people to improve their lives (LEWIS, 1955), wellbeing from a development perspective continued to be centered on economic growth.

3.2.2. Multi-dimensional conceptualizations: seeking a coherent theory of wellbeing

The shift towards a multidimensional conceptualization of wellbeing only started to occur in the 1960s, as development thinking became associated with equitable growth and social objectives, especially poverty alleviation (MUNASINGHE, 2003). As such, ideas around what constitutes wellbeing started to evolve from a narrow focus on objective measures of economic conditions (i.e. basic needs like housing, education, sanitation) to include a range of non-economic factors (e.g. social, cultural,

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[47] However, according to empirical studies, absolute convergence has only been found in developed countries (e.g., BAUMOL, 1986; BARRO, 1991; BARRO AND SALA-I-MARTIN, 1992).

[48] This hypothesis was criticized by new growth theories developed in the 80s and 90s (e.g. LUCAS, 1988; ROMER, 1990; REBELO, 1991). For a review of contemporary economic growth models and theories see SHARIPOV (2015).

psychological).

The publication of *Social Indicators* by Bauer in 1966 and *The Meaning of Development* by Dudley Seers in 1969 started the debate into basic human needs– physical necessities such as food, shelter and public goods, as well as the means to acquire these (SUMNER, 2004), and how the satisfaction of them is linked to wellbeing and development. The number of published papers on wellbeing and life satisfaction increased sixty fold between 1961 and 2005 (DIENER, 2008). This upsurge was partly a result of the persistence of poverty around the world, as well as of a two-fold realization (1) that the benefits of economic growth did not trickle down according to data on health and education (SUMNER, 2004), and (2) that beyond a rather modest income level, individual wellbeing is not associated with continuing growth in real incomes (EASTERLIN, 1974).

In the early 1970s, sociologist Erik Allardt developed an illustrative multi-dimensional conceptualization of human wellbeing in which he defined "the central necessary conditions of human development and existence" in three words: having (associated with material conditions necessary for survival and to avoid misery), loving (associated with the need to relate to other people and to form social identities), and being (associated with the need for integration into society and to live in harmony with nature) (see ALLARDT, 1976). As such, Allardt's approach was the first one to encompass non-material aspects of wellbeing that, although having had their existence acknowledged by the Marginalist Welfare School, had been dismissed as deserving of attention by economists, primarily due to the difficulties associated with their quantification.

A host of other multi-dimensional conceptualizations of wellbeing were developed since then, including the capability approach (e.g. SEN, 1985, 1999a, 1999b, and 2003), the human development approach (UNDP, 1990), the intermediate human needs approach (DOYAL AND GOUGH, 1991 and 1993), the axiological categories approach (MAX-NEEF, 1993), the universal human values approach (SCHWARTZ, 1994), the multidimensional wellbeing approach (NARAYAN *et al.*, 2000), the human rights-based approach[49] (UNGA, 1986 and 2000), and the central human capabilities approach (NUSSBAUM, 2000). The most recent conceptual frameworks around wellbeing have also attempted to demonstrate the linkages among ecosystem services and human wellbeing (e.g. MEA, 2005; COSTANZA *et al.*, 2007). These increasingly complex and multi-dimensional conceptual approaches have identified different dimensions and domains according to their disciplinary area that can be social, physical, psychological or material in nature (ALKIRE, 2002).

Arguably, the capability approach originated by economist Amartya Sen and philosopher Martha Nussbaum, has been the most influential in shifting the conceptual understanding of wellbeing (MCGILLIVRAY, 2007). Drawing on the basic needs approach associated with Paul Streeten (STREETEN *et al.*, 1981), this approach gave greater emphasis to functionings (i.e. set of things people are and do), the role of freedom (i.e. autonomy, agency), and people's capabilities (all their potential functionings, i.e., what they can be and do in their life) (SEN, 1985, 1995, and 1999). By reinstating the focus on what humans beings can do instead of what they have, it broke away from the prevailing utilitarian approach to wellbeing remitting to earlier conceptions of wellbeing, all the way back to Aristotles' *eudaimonia*, discussed in section 2.1.2 (SEN, 2003).[50]

The capability approach has been used as a conceptual framework in the Human Development Reports, a series of yearly reports on human wellbeing published by the UNDP since 1990 (SUMNER, 2002). The process of development was then generally understood to be not simply about meeting basic needs but about enhancing human freedom and capability, emphasizing the importance of ends (like a decent standard of living) over means (like income per capita) (SEN, 1985). More recently it has been contemplated as a potential conceptual framework for sustainability assessment and sustainable development (e.g. BALLET *et al.*, 2011 and 2013; MARTINS, 2011;

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[49] What is now termed the rights-based approach to development has a relatively recent history in the discourse of international development agencies, emerging in the post-Cold War period in the early 1990s, and gathering momentum in the build up to the Copenhagen Summit on Social Development in 1995 (MUSEMBI AND CORNWALL, 2004).

[50] For an examination of the Aristotelian approach and its relation to contemporary works on functionings and capabilities, see NUSSBAUM (1987).

LESSMANN AND RAUSCHMAYER, 2013; VOGET-KLESCHIN, 2013),[51] as the ecological embeddedness of wellbeing started to gain broader recognition. Although, it is not clear how inter-generational justice and responsibilities could be incorporated to society, nature and future generations[52] using the capability approach (RAUSCHMAYER AND LEBMANN, 2011).

Despite the international attention drawn towards sustainability and sustainable development during the late 1980s with the publication of Our Common Future in 1987 (WCED, 1987),[53] and particularly following the 1992 Earth Summit in Rio, the traditional vision of environment as a limit to economic growth has slowly shifted towards the recognition of its active role in achieving higher living standards and increasing human development levels. Only more recent editions of the Human Development Report have considered the role of the natural environment in enhancing people’s choices, and even presented ancillary indicators on the consumption of natural resources. However, they have yet to incorporate environmental indicators into their headline indicator, the HDI (MORSE, 2003).

Perhaps the most comprehensive work guiding the understanding and measurement of human wellbeing within the wider context of the socio-ecological system is the conceptual framework provided in the Millennium Ecossystem Assessment (MEA, 2005) (MOONEY *et al*., 2004, also cited in KING *et al*., 2014). However, there is still a significant methodological gap in the valuation of ecosystems configurations (BARBIER, 2007).

More recently, human wellbeing has also been examined under a capital-based approach, whereby income or consumption is seen as one of different factors that contribute to the production of wellbeing (MULDER *et al*., 2005; VEMURI AND

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[51] See, particularly the special issue on ‘Capability and Sustainability’ of the Journal of Human Development and Capability, volume 14, 2013.

[52] Sustainable development requires the same level of wellbeing achieved for the present generation to be maintained for future generations (WCED, 1987).

[53] Also known as the Brundtland Report, it was published by the World Commission on Environment and Development (WCED) and became a landmark publication calling for economic development that would guarantee “the security, wellbeing, and very survival of the planet” (WCED, 1987). It coined the modern-day definition of the term “sustainable development”, namely: "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The WCED had been established in 1983, as a special commission to address the rapid deterioration of the human and ecological environments.

COSTANZA, 2006; OSBERG AND SHARPE, 2011). According to this approach, wellbeing measurement encompasses manufactured or built capital (e.g. infrastructure and financial resources), natural capital (e.g. energy resources, mineral resources, land, ecosystems and biodiversity, water, air quality and climate), human capital (e.g. health, education, and labor), and social capital (e.g. trust, social networks, and institutions). The idea of maintaining the value of total capital intact is believed to operationalize the notion of maintaining the capacity to provide non-declining wellbeing over time (NEUMAYER, 2004).

All multi-dimensional conceptualizations of wellbeing developed since the 1970s, and primarily since he last three decades, have increased awareness and recognition of the combined effects of social, economic, and environmental factors on the achievement of collective wellbeing (SUMMERS *et al.*, 2012). However, in spite of all the work put forth to date, no alternative approach to wellbeing has been able to replace the prevailing neoclassical narrative. WHITBY *et al*. (2014) suggest that a stronger theoretical foundation is still needed. Given their complexity and multi-dimensional nature, integrating the existing conceptual approaches into a coherent theory of wellbeing will require an unprecedented massive effort (CARPENTER *et al*., 2009).

3.3. Traditional measurements: GNP, GDP, GNI

In line with the prevailing utilitarian approach to wellbeing discussed above in section 3.2.1, the focus on Keynesian approaches towards post-war recovery and economic growth and the presence of national accounting tools fostered the use of major aggregates of national income and product accounts, like GDP, as a measure a country’s wellbeing and development.

Based on estimates and survey data maintained in System of National Accounts (SNA), GDP estimates the total economic production, usually representing the market value of all goods and services produced within a geographical entity within a given period of time (GOOSSENS *et al*., 2007; COSTANZA *et al*., 2009). It aggregates personal consumption expenditures (payments by households for goods and services), government expenditures (public spending on the provision of goods and services, infrastructure, debt payments, etc.), net exports (the value of a country's exports minus the value of imports), and net capital formation (the increase in value of a nation's total stock of monetized capital goods) (COSTANZA *et al*., 2009). This means that all production is summed in terms of their market value (i.e. price), where only the value of final goods is included, as opposed to including the value of all intermediate sales.

The GDP can be expressed on the basis of expenditure or income. Based on expenditures, it is calculated as follows (ANIELSKI, 2002):

GDP = personal consumption expenditures (of households)
+ government expenditures
+ government investment in fixed capital
+ business investment in fixed capital
+ investment in inventories
+ exports of goods and services
- imports of goods and services

Detailed economic data collected through censuses and surveys became available through national accounting systems developed in response to the need to better understand the Great Depression and later to aid in the conduct of the Second World War.[54] After the Second World War, when the economics of development was targeting reconstruction and capital accumulation, these data were further used to help understand how and in what ways economic growth could be promoted. The focus then shifted from national income to Gross National Product (GNP) and later on to Gross Domestic Product (GDP), which became the most widely accepted measure of a country's economy, and to a large extent, of its wellbeing and development (COSTANZA *et al*., 2009; VAN DEN BERGH, 2009; DICKINSON, 2011).

While the debate on economic growth concepts and theories may have influenced this practice, [55] it did not result from any specific economic theory on the use of GDP as a measure of wellbeing (VAN DEN BERGH, 2009). However, it coincides with the fact that after the SNA was adopted and regular GNP (and later GDP) reporting to the United Nations was requested, not only international and inter-temporal

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[54] The accounts enabled both the US and, in a slightly different setting, also the UK, to locate unused capacity in the economy and to exceed conventional production levels by far (GOOSSENS *et al*., 2007).

[55] See SHARIPOV (2015) for a discussion on contemporary theories and models of economic growth.

comparisons were disseminated but concerted focus on economic growth was created. The development of GNP and GDP is, thus, embedded within the history of national income and product statistics, a summary of which is provided next.

3.3.1. A brief history of national income and product statistics

National income estimates date back to the 17th century with the works of Sir William Petty in England and Pierre le Pesant de Boisguilbert (or Boisguillebert) in France (STUDENSKI, 1958). Since then, the development of national income estimation can be divided roughly into two main periods, a larger one lasting through the First World War and a shorter one starting after that war (KENDRICK, 1970).[56] In the first period, national income estimates were prepared by a succession of scholars in few advanced countries, primarily motivated by the desire to compare the economic strength of nations, as well as the need to understand how the tax system could be made more equitable and even more revenue-producing, to show how much resources could be mobilized for war, or to develop the policies needed to strengthen and reform national economies, i.e. to promote economic growth. The second period was characterized by a self-sustaining institutional development of national income statistics that spread to virtually all countries, aimed at promoting the development of underdeveloped nations and to meet the statistical requirements of the United Nations.

According to KENDRICK (1970), the United States was the fourth country in which national income estimates appeared, after England, France and Russia. In England, the pioneering estimates of Sir William Petty presented in 1665 were improved by his immediate successor, Gregory King, whose computations published in 1696 resembled a national balance sheet prefiguring modern social accounts (STUDENSKI, 1958). In a time when England was in the throes of a continuing struggle with France and Holland, Petty and King were both motivated by the need to determine England’s taxable capacity and to compare the country’s material strength with that of the other two countries (STUDENSKI, 1958; KENDRICK, 1970). A

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[56] The historical development of national income estimation presented in KENDRICK (1970) is heavily based on the work of Paul Studenski (STUDENSKI, 1958), as noted by that author. Both authors present an extremely detailed account of the early works around national income estimation and are thus the primary references used in this section of the thesis.

different motivation led Pierre Boisguilbert, a French economist, to publish the first national income estimates for France in 1697. He was convinced of the need for tax reform and for a general liberalization of governmental policy toward economic life (STUDENSKI, 1958). However, because he failed to provide appropriate sources and methods for his work he is not regarded as the founder of the statistical approach to national income in France. Instead, that title was given to Marshal Vauban, who in 1707 published estimates of income aimed at calculating the amount of revenue that would be raised at various rates in support of his proposal of a universal, proportional gross income tax (KENDRICK, 1970).

Income estimates were developed much later in Russia. The 18th century marked a time of rapid economic, social and cultural progress in a comparatively liberal Russia that favored economic inquiries (KENDRICK, 1970). Systematic statistical collections that had begun in 1718 provided the basis for the first national income estimates for Russia, published in 1790 in German by B. F. J. Hermann, an Austrian mineralogist.

By the beginning of the 19th century income had already been estimated by all three major approaches: factor income, final expenditure, and income originating (value added) by industry (KENDRICK, 1970). After the enactment of an income tax in the 1840s, income tax records were used as primary source for national income estimation in Great Britain up until the First World War. They provided more reliable data than production data did. In France, while more income estimates were produced than in England during that century, their statistical basis was deemed weaker because there was no income tax data yet (KENDRICK, 1970). In Russia, there are no records of new estimates before the very end of the 19th century.

The first attempt to estimate annual income or product in the United States was made in 1843 by George Tucker, professor of moral philosophy at the University of Virginia. He based his estimates at first on six decennial censuses taken between 1790 and 1840 and later on including the 1850 census (STUDENSKI, 1958). Although not comprehensive, his estimates on the net value (value added) of commodity output by industry and by state were consistent and carefully done (KENDRICK, 1970).

The second half of the 19th century and the first years of the 20th century saw national income estimates prepared by several other countries for the first time, including Austria, Germany, Australia, Norway, Japan, Switzerland, Netherlands, Italy, and Bulgaria (STUDENSKI, 1958). Notably the first official estimation under governmental auspices appeared in Australia in 1886, prepared by Timothy Coghlan, the first modern estimator to embrace all three aspects of national income- its production, distribution, and disposition (STUDENSKI, 1958) and to make use of the estimates to reveal significant economic trends and relationships (e.g. per capita income, functional income distribution, and real-income trends) (KENDRICK, 1970).

The beginning of the second period of national income development was marked by the switch from scholars and individual investigators to institutional producers of estimates and the worldwide spread of economic accounting, from thirteen in 1919 to thirty-three countries in 1939 (STUDENSKI, 1958). During the First World War and the 1920's organizations and governments gradually took over as producers of national income statistics, as interest in these figures spread (CARSON, 1975). In the United States, the Great Depression along with the development of macroeconomic theory, and the prospect of using national income estimates as a background for more effective countercyclical policies stimulated a thorough institutional development of income statistics (KENDRICK, 1970; VAN DER BERGH, 2009; COSTANZA *et al*., 2009 and 2014). In 1932, at the depth of the Depression, Congress commissioned Simon Kuznets to create a system that would measure the nation's productivity continually on a regular basis aimed at helping understand business cycles in general and the Great Depression in particular.[57]

Kuznets started his pioneering work in continuing series of national income and its components at the National Bureau of Economic Research in the spring of 1933 rendering the first publication of national income estimates in 1934 (KUZNETS, 1934). Kuznets' national accounts served as the basic frame for national income estimates for more than a decade (CARSON, 1975) and a rich source of statistical information, which became invaluable to assist in understanding the Great Depression and in devising

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[57] Simon Kuznets was an economist at the United States National Bureau of Economic Research and later Nobel Prize winner for his work, who became known as the father of national income accounting in the United States (ATKINSON, 2012). His main interest was to measure the levels of industrial and agricultural production and to understand how much of the national income was due to consumption and investment.

countercyclical policies. Later on his measures were used to calculate gross national product (GNP), an aggregate that measured final purchases by households, business, and government, arrived at by adding to national income, which Kuznets estimated as the aggregate of all income paid to individuals, plus net savings of all enterprises, the amounts previously deducted as representing the current consumption of durable capital goods (KUZNETS, 1937). By the late 1930's quantitative analysis using national income estimates became more sophisticated, reflecting the impact of macro-economic theory, the greater detail in the available estimates, and the lengthened time span over which consistent series were available (CARSON, 1975).

However, with the start of the Second World War in 1939, the economic challenges faced by the United States and all the countries involved in the war changed completely. Concerns over causes of economic slow downs (e.g. excess savings, buildups in capital stock) were replaced by concerns over war finance problems and inflationary potential (ATKINSON, 2008). Meanwhile, government economists argued that national income was not the most appropriate aggregate for comparisons with and calculations relating to war expenditures, given that such expenditures largely consist in purchases of current output of goods and services, measured in terms of market prices (CARSON, 1975). As such, estimates of "gross national expenditure at market prices", which gradually evolved to Gross National Product (GNP), were introduced in the early 1940s to provide information about major categories of expenditures in the economy to assist with wartime planning (CARSON, 1975; ATKINSON, 2008).[58] Both in England and in the United States, income and expenditure were looked on as the two sides of a double-entry production account for the entire national economy (KENDRICK, 1970).

After the Second World War, the focus on production data and use of GNP (and later GDP) as a measure of economic progress spread globally, in particular after the Bretton Woods Conference in 1944. At this conference, leaders of all 44 allied nations created a process for international cooperation on trade and currency exchange to promote economic growth and thereby foster world peace (COSTANZA *et al.*, 2009). The variables that were behind GNP were considered of crucial importance in

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[58] As noted in CARSON (1975), the addition of indirect business taxes to national income and the related decision to include as final product all government output were significant departures from Kuznets' pre-war concept of gross national product.

monitoring and promoting economic growth.

Also in 1944, representatives of British, American, and Canadian national income agencies met in Washington to discuss concepts and modes of presentation to make their national income estimates comparable and more useful to their governments (KENDRICK, 1970). This initiative resulted in the creation of the System of National Accounts (SNA), an integrated set of international guidelines for the production of national income statistics that have been published and updated by the United Nations since 1953.[59] Even though the calculation of GNP and other aggregates for the total economy was not the main reason for compiling national accounts they have been widely used for international comparisons (CEC *et al.*, 1993). In 1956, the UN requested national accounts data, including GNP, to 77 countries (MCNEELY, 1995). After 1970 the SNA shifted the emphasis to GDP as the primary aggregate of interest. In 1975, 108 countries, out of 113 surveyed, reported GDP data to the UN. In the United States the shift to GDP only took place in 1991 (BEA, 1991).

More recently, there has been a move back to the use of “national” as opposed to “domestic”. In 2010, inspired by new research by development economists, the UN moved away from GDP and instead adopted Gross National Income (GNI) per capita as its primary measure of economic wellbeing in calculating its Human Development Index (UNDP, 2010).[60] Otherwise, GDP has maintained a firm position as a dominant economic indicator, even though it has been severely criticized for not capturing human wellbeing and development adequately (COSTANZA *et al.*, 2009, VAN DEN BERGH, 2009; among others), as discussed in the following section.

3.3.2. Shortcomings of GDP as a measure of societal wellbeing

As wellbeing conceptualizations evolved from the narrow focus on objective measures of economic conditions towards more complex and multi-dimensional interpretations encompassing the many different aspects of human life, as discussed in

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[59] SNA publications are available in the National Accounts Section of the United Nations Statistics Division at: http://unstats.un.org/unsd/nationalaccount/sna.asp.

[60] Gross National Income refers to the sum of value added by all residents of a country. It is equal to GDP minus primary income payable by residents to non-residents, plus primary income receivable from the rest of the world (from non-residents to residents) (UNDP, 2010).

section 3.2, several streams of thought have highlighted the shortcomings of GDP as an indicator of societal wellbeing. It has been widely suggested that it is an inaccurate and misleading gauge of prosperity, and as such, it should not be relied upon as the sole means of determining the wellbeing of a nation.

The shortcomings of GDP as a measure of societal wellbeing have been know since soon after its introduction (COSTANZA *et al.*, 2009).[61] In its 1934 report to Congress, Simon Kuznets, GNP's chief architect cautioned that the "welfare of a nation can scarcely be inferred from a measurement of national income" (KUZNETS, 1934). His intent was for GNP (and later GDP) to be a specialized tool, designed to measure only a narrow segment of society's activity (COSTANZA *et al.*, 2009). Three decades later, concerned about the extensive use of GNP as a measure of progress and development, Kuznets further remarked that "distinctions must be kept in mind between quantity and quality of growth, between its costs and return, and between the short and long run" and that "goals for more growth should specify more growth of what and for what" (KUZNETS, 1962).

Another cautionary note came from U.S. President Robert F. Kennedy during his presidential campaign trail in 1968, when he stated that GNP "measures everything, in short, except that which makes life worthwhile".[62] In 1999, economist John Kenneth Galbraith remarked that "there is a major flaw in measuring the quality and achievement of life by the total of economic production – (GNP/GDP) – the total of everything we produce and everything we do for money."[63] More recently, in 2012, former U.S. Federal Reserve Chairman Ben Bernanke reasoned that GDP is "useful for monitoring people's ability to meet basic material needs and for tracking cyclical and secular changes in the economy as a whole. … [But] …we should seek better and more-direct measurements of economic wellbeing, the ultimate objective of our policy decisions".[64]

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[61] All the shortcomings of GDP as a wellbeing indicator discussed here apply equally to GNP.

[62] Robert F. Kennedy's 1968 Address at the University of Kansas in 1968: http://www2.mccombs.utexas.edu/faculty/michael.brandl/main%20page%20items/Kennedy%20on%20GNP.htm

[63] Review of John Kenneth Galbraith's address to the Frank M. Engle Lecture in Economic Security at the American College in Bryn Mawr, Pennsylvania in May 1999, appeared in the August 2, 1999 issue of the IMF Survey (IMF, 1999).

[64] Bernanke's speech at the 32nd General Conference of the International Association for Research in Income and Wealth, Cambridge, Massachusetts on August 6, 2012: http://www.federalreserve.gov/newsevents/speech/bernanke20120806a.htm

The extensive use of GDP to indicate more than it was designed to do reflects the narrow focus on economic growth that has prevailed since the end of the Second World War, as discussed in sections 2.4.1, 3.2.1 and 3.3.1 in the text. The implicit and explicit interpretations and use of GDP as a proxy for real wellbeing of nations have received much criticism from some of the most respected economists, including various Nobel laureates (see for instance COSTANZA *et al*., 2009, STIGLITZ *et al*., 2009; OSBERG AND SHARPE, 2011; PIKETTY, 2014; ADLER AND SELIGMAN, 2016).

Generally speaking the key argument for GDP’s inappropriateness as a measure of societal wellbeing and development lies on the fact that measuring a country’s wellbeing solely in economic terms misses the key fact that the economy is a means to an end, not an end in itself. As such, GDP does not capture other intrinsic domains and dimensions of wellbeing, such as the value of non-market goods and services (e.g. ecosystem services, household work, and leisure), health and quality of life, and social networks and relationships. The many criticisms discussed in the literature can be grouped in at least six broad categories, as presented below:

1. Informal/or and non-market activities and services are not included

GDP only covers activities and services that occur inside formal markets and/or are paid for, i.e. that have a market price. By measuring only marketed activities and services, GDP is based on an incomplete picture of the system within which the economy operates (COSTANZA *et al*., 2009). It fails to include several activities that even though do not have market value represent key aspects of collective wellbeing such as subsistence farming, household work, childcare, care for the elderly and the ill, other types of voluntary work, ecosystem services, leisure and even education. Meanwhile, a transfer of some of these informal activities to a formal market would typically result in a higher GDP but no change in wellbeing (GOOSSENS *et al*., 2007, VAN DEN BERGH, 2009). This means that the benefits would have already contributed to wellbeing but the market costs were not yet taken into consideration within the GDP calculation. Notably, from the GDP perspective, leisure entails “opportunity costs” as each unit of leisure is a potential but "lost" increase of GDP (GOOSSENS *et al*., 2007). Moreover, because GDP does not recognize the value of informal activities and services, these are often cut back and discouraged by public policy (VAN DEN BERGH, 2009). The extent of this problem depends on the size of the informal economy relative to the total human activity and production, therefore it is typically more pronounced in the developing world (see SCHNEIDER, 2002).

2. Income distribution is ignored

The GDP per capita indicator emphasizes average income and neglects changes in income distribution, as it implicitly puts higher weight on the expenditures of the wealthy (through their bigger share in the overall consumption and investment) rather than on income development of the poor. This was one of the main criticisms of Amartya Sen (SEN, 1976) to GDP as a measure of societal wellbeing (welfare).[65] An uneven income distribution implies unequal opportunities for personal development and wellbeing (VAN DEN BERGH, 2009). Furthermore, individuals or families with low incomes benefit relatively more from an income rise than those with higher incomes, because of the diminishing marginal utility of income (VAN DEN BERGH, 2009). Meanwhile, while an increase in relative income may improve the wellbeing of an individual, it will not necessarily improve the collective wellbeing. GDP per capita does not capture these features.[66] Similar to the previous item, this shortcoming is of greater concern to the developing world where income inequality is more prominent.

3. Benefits of a healthy society are not taken into consideration

Changes in the health conditions of a society are only reflected in GDP in so far as they increase the costs of the health system (GOOSSENS *et al.*, 2007). As such, a healthier population does not necessarily translate into a higher GDP. Conversely, a more expensive health care system would directly increase GDP through cost growth. Of greater concern is the fact that higher expenditure in narcotics, alcohol or other harmful substances to human health translates into an increase in a nation’s GDP. Similar distortions also take place in regard to violence. An increase in crime rates

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[65] SEN (1985) noted that, when collective wellbeing (welfare) was measured as GDP nations were then divided into ‘haves’ and ‘have-nots’, i.e. ‘rich’ and ‘poor’.

[66] According to STIGLITZ (2005), median rather than average GDP would serve a better job in capturing inequality.

represents an indirect increase in GDP, as greater expenditure with security systems would take place.

4. The threshold effect: decreasing gains after a certain level of GDP per capita

There is an increasing body of research confirming that beyond a certain threshold, further increases in GDP does not lead to increases in wellbeing, in view of negative side-effects of lowering other dimensions of human wellbeing like community cohesion, healthy relationships, knowledge, and wisdom (MAX-NEEF, 1995; TALBERTH *et al*., 2007). According to KATE *et al*. (2006), as people move away from a subsistence level provided by a certain level of GDP per capita the relationship between income level and perceived happiness simply disappears, as depicted in Figure 10 below.

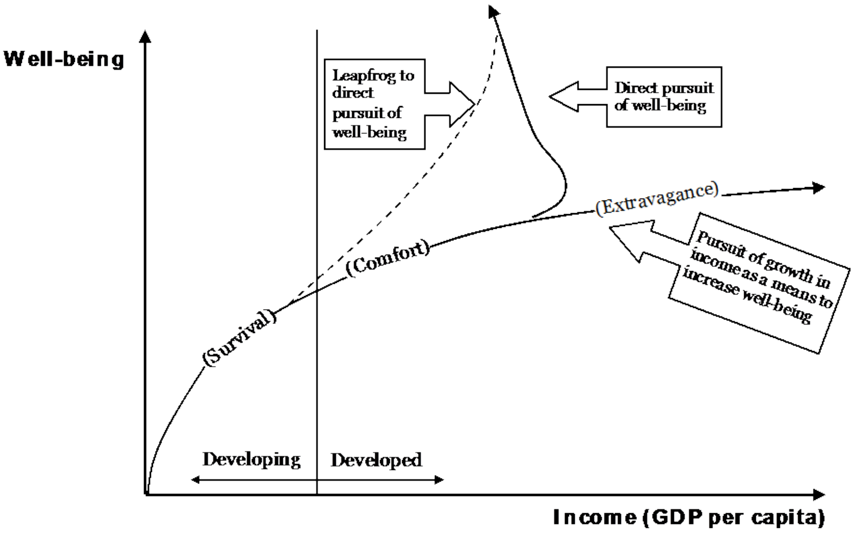

Figure 10 - Income (in per capita GDP) versus wellbeing.

Source: STUZT (2006).

There is a vertical line marking the border between the realm of development in which gains in income yield substantial gains in wellbeing and the developed realm where the gains become minimal. Past that line, and beyond the level of income required for comfort, one reaches a “fork in the road”. The lower and upper branches of the solid curve that follow the fork illustrate different approaches to the pursuit of wellbeing. Those following the bottom branch seek additional wellbeing as a by-product of gains in income, while those following the upper branch pursue wellbeing directly. They make choices such as limiting their hours of paid work to make time for a range of unpaid activities that allow them, in Keynes' words, "to live wisely and agreeably and well" (STUZT, 2006).

SMIL (2000) describes a similar dynamic between rising per capita energy use and a higher physical quality of life measured by adequate health care, nutrition, and housing. He shows that increased energy use beyond a certain range has been associated with rapidly diminishing improvements of physical quality of life, noting that energy use above a certain level is spent overwhelmingly on more ostentatious consumption and more frequent pursuit of high-energy, and often environmentally destructive, pastimes ranging from transcontinental flights to desert casinos to snowmobile runs through national parks. This pattern matches the lower branch of the solid curve that follows the fork illustrated in Figure 9 above.

5. Environmental degradation and resource depletion are ignored

The degradation of ecosystem services often represents a loss of a natural asset of a country, which often affects wellbeing, both directly and indirectly (UNU-IHDP AND UNEP, 2014). However, such loss is not reflected in GDP. Based on the GDP perspective, if a country cuts its forests and depletes its fisheries this would show only as a positive gain without registering the corresponding decline in natural assets. The presence of environmental externalities means that the current set of market prices insufficiently reflects the total costs, which makes these prices unreliable signals in whatever calculation aimed at producing a social welfare indicator (VAN DEN BERGH, 2009).

GDP does not include costs associated with any damage from pollution; however, expenses incurred with any associated cleanup will lead to an increase in GDP. Two environmental disasters, the Deepwater Horizon oil spill in 2010 and Hurricane Sandy in 2012, are good examples of this perverse practice. Despite the degradation and losses they caused, both events boosted US GDP because they stimulated rebuilding (COSTANZA *et al*., 2014). Moreover, the depreciation associated with environmental changes (fish stocks, forests, biodiversity) and depletion of natural resource supplies is missing from the GDP calculation. As a result, we are considering ourselves ‘richer’ than we really are (ATKINSON *et al*., 1997).

Because GDP does not distinguish between ‘good growth’ and ‘bad growth’ it is providing an incentive for unsustainable resource use. Another fundamental consequence of neglecting sustainability of natural capital is the distorted perception that substitution of basic conditions by market goods equates to progress. This in turn unnecessarily encourages the replacement of nature by market economy.

6. Inconsistent accounting principles

From an accounting perspective, STIGLITZ (2005) compared a country to a firm arguing that "no one would look just at a firm's revenues to assess how well it was doing. Far more relevant is the balance sheet, which shows assets and liabilities. That is also true for a country." In this sense one important bookkeeping principle is violated in GDP: the division between assets (benefits) and liabilities (costs). Whereas firms employ separate accounts for benefits and costs, GDP adds them together. The use and calculation of the GDP (per capita) indicator is inconsistent with two other principles of good bookkeeping: (a) correct for changes in stocks and supplies, and (b) use accurate measures for all social costs (VAN DEN BERGH, 2009).

GDP focuses on current economic activities or flows, rather than on the developments in natural, economic and social capital assets, which are important from a long-term perspective (VAN DEN BERGH, 2009). As such, declines in stocks that represent value or welfare are not taken into account (e.g. natural gas in the earth). Because it measures only flows, not stocks, the consumption of non-renewable natural resources such as oil counts as an addition to GDP, while the remaining stock of oil reserves is not valued as a stock. Natural resources should be treated as stocks that are drawn down when they are extracted and used. This would result in a clearer picture: when resources are discovered, they would be added to the “wealth” of the country, and subtracted as they are drawn down.

3.4. New measurements: alternative indicators to GDP

In view of the criticisms to the use of GDP as a proxy for national wellbeing discussed above, national and international institutions, research centers, and various researchers have stressed the need for a new measurement system for human wellbeing from a development perspective focused on social and economic welfare of both present and future generations (COSTANZA *et al.*, 2009; VAN DEN BERGH, 2009; DICKINSON, 2011).[67]

Recent examples of national and international efforts toward new multi-dimensional approaches to measure national wellbeing include Bhutan's pursuit of Gross National Happiness (GNH), the recommendation by the United Nations Secretary-General's global sustainability panel to establish a set of indicators to measure progress toward sustainable development, the so-called 'satellite account systems' that complement the conventional statistical national accounts with environmental and/or social information (U.S. BEA, 1994; CEC, 2009), work by statistical authorities on "national wellbeing" in the United Kingdom, the European Commission's "Beyond GDP" project, and the Organization for Economic Co-operation and Development's (OECD) Better Life Initiative[68] (Royal Government of Bhutan, 2012).

The need for a new measurement had already become explicit about three decades ago, as ideas around what constitutes wellbeing started to evolve from a narrow focus on objective measures of economic conditions (i.e. basic needs like housing, education, sanitation) to include a range of non-economic factors (e.g. social, cultural, psychological) leading to a host of new multi-dimensional conceptualizations of wellbeing, as discussed in section 3.2.2.

A number of new ways to measure societal wellbeing have come forward to address the growing realization that GDP is solely a measure of economic quantity, not economic quality or wellbeing, let alone social or environmental wellbeing

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[67] In 2011, 193 Member States of the United Nations General Assembly agreed "to pursue the elaboration of additional measures that better capture the importance of the pursuit of happiness and wellbeing in development with a view to guiding their public policies" (UNGA, 2011).

[68] The Better Life initiative draws on the themes identified by the Commission on the Measurement of Economic Performance and Social Progress (CMEPSP), also known as the Stiglitz-Sen-Fitoussi Commission, established by the French government in 2008. The CMEPSP published a final report in September 2009 (STIGLITZ *et al.*, 2009).

(COSTANZA *et al*., 2009). These include new aggregate indicators[69] that encompass education achievements, health outcomes and/or environmental degradation among other aspects that GDP failed to take into account. Notably, empirical research advanced towards quantification of human wellbeing despite the lack of a strong theoretical foundation around human wellbeing and guidance on how to develop an appropriate metric.

Figure 11 below depicts a timeline of the main alternative indicators that encompass the three dimensions of wellbeing under the sustainable development concept - economic, environmental, and social (except for HDI) – into a single number (that result from combining and weighing of individual variables), usually expressed in monetary terms. One of the earliest such attempts was the Measure of Economic Welfare (MEW) proposed by Nordhaus and Tobin, in 1972 (NORDHAUS AND TOBIN, 1972). However, the majority of the new methods and indicators proposed in the academic literature came forth after the concept of sustainable development made an international breakthrough with the publication of the Brundtland Report in 1987 (WCED, 1987).[70]

These indicators can be grouped in a number of different ways, for example: by the issue areas they cover or by the way the indicators are constructed (e.g. COSTANZA *et al*., 2014). KING *et al*. (2013) distinguish alternative indicators (and other initiatives) among three broad categories: subjective, objective, and mixed methods approaches. These approaches do not refer to methods of measurement (self-report or ascribed), rather to what is being measured: whether feelings (subjective/qualitative attributes) or non-feelings (objective/quantitative attributes).

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[69] The term ‘aggregate indicator’ in the context of this paper refers to an indicator that has been obtained by combining and weighing of individual variables/indicators that reflect different human wellbeing dimensions that can exist on their own, separately from the aggregate indicator.

[70] See footnote 53.

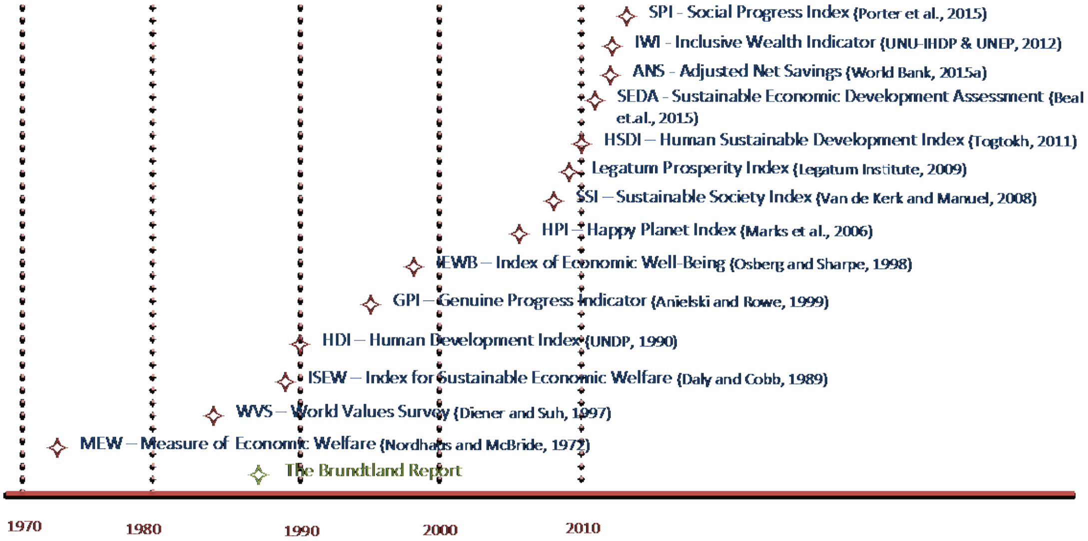

Figure 11 - Timeline of Key Alternative Indicators to GDP.

Source: Prepared by the author.

The subjective approach attempts to measure life satisfaction or people’s moods and emotions (DIENER AND SUH, 1997; GASPER, 2004 and 2005). They typically entail self-assessments through survey questions asking respondents to place themselves on scales that rate their satisfaction or happiness (MCALLISTER, 2005). The objective approach uses objective components, those physical or socio-economic factors that are deemed to contribute or detract from individual or collective wellbeing and are easily measured at the population level based on quantitative statistics, such as physical resources, employment and income, education, health, and housing (TALBERTH *et al.*, 2007, KING *et al.*, 2013). The mixed methods approach reflects a combination of the former and latter approaches, whereby qualitative attributes are used to supplement as well as assist in the development of quantitative measures that more adequately reflect the complex and multi-dimensional nature of human wellbeing (KING *et al.*, 2013).

In this study we group them by their approaches towards GDP, as defined in GOOSSENS *et al*. (2007) and SCHEPELMANN *et al*. (2010), and elaborated further below: *the replacing approach, the adjusting approach, and the supplementing approach* (see table in Appendix B).

3.4.1. Aggregate indicators using the *replacing* GDP approach: HDI, HSDI, and HPI

Those indicators that use the *replacing approach* would try to assess wellbeing more directly than GDP, e.g. by assessing the achievement of basic human functions (like the Human Development Index and the Human Sustainable Development Index) or average satisfaction (like the Happy Planet Index). Advocates of the use of indicators that replace GDP can argue that GDP is not and was never meant to serve as a measure of societal wellbeing (COSTANZA *et al*., 2009).

The Human Development Index (HDI):

Economists Amartya Sen and Mahbub ul Haq, the latter from the United Nations Development Programme (UNDP), presented the Human Development Index (HDI) in 1990. The HDI follows the *replacing* GDP approach. HDI is a measure of human development that combines proxies for three important dimensions: health (represented by life expectancy), education (represented by mean years of schooling and expected years of schooling), and a decent standard of living (represented by GNI per capita),[71] as follows (KLUGMAN *et al*., 2011):

$$\mathbf{HDI} = I_{Life}^{\,1/3} \text{ x } I_{Education}^{\,1/3} \text{ x } I_{Income}^{\,1/3}$$

Where:
I_{Life} = life expectancy index
$I_{Education}$ = Education index
I_{Income} = GNI index

$$\text{Each dimension index} = \frac{\text{(actual value - minimum target value)}}{\text{(maximum target value - minimum target value)}}$$

Following the technical notes of the Human Development Report 2013 (UNDP, 2013), each of these dimensions is represented by a specific sub-index computed as where x is the observed value for a given country. It sets a minimum and a maximum for each dimension and then shows where each country stands in relation to them,

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[71] The indices are relative and normalized, such that for each component is calculated with respect to the minimum value in the sample, and then normalized to the maximum difference found in the sample. A country potentially having the highest score across all three dimensions would have an HDI value of 1.0.

expressed as a value between zero and one, based on their geometric mean (GOOSSENS *et al.*, 2007).[72] The three dimension indexes are computed separately and the HDI is simply their geometric mean. Since all three sub-indexes fall by construction between zero and one, the HDI is limited in the same interval with greater values indicating higher development levels. The HDI uses readily accessible source of data across 187 countries (UNDP, 2013), is based on a reasonably consistent basis since 1990, and should continue to be available in the future (PERMAN *et al.*, 2003). Its major criticism, as noted in section 2.4.2, refers to the fact that it does not consider the environmental dimension or the intergenerational equity principle.

The Human Sustainable Development Index (HSDI):

The HSDI was first proposed by TOGTOKH (2011) in an attempt to address HDI's failure to encompass the environmental dimension by adding a fourth sub-index based on per capita CO_2 emissions. This sub-index is computed differently from the original ones, though. The emissions index is calculated by taking the complement to one of the original equations to reflect the fact that higher emissions mean a poorer environmental performance. The maximum target value corresponds to the highest observed value in the period of assessment and the minimum is set to zero, i.e., representing a fully decarbonized economy (BRAVO, 2014). The HSDI is calculated, thus, as follows:

$$\mathbf{HSDI} = I_{Life}^{\,1/4} \times I_{Education}^{\,1/4} \times I_{Income}^{\,1/4} \times I_{Emissions}^{\,1/4}$$

Where:
I_{Life} = life expectancy index
$I_{Education}$ = Education index
I_{Income} = GNI index
$I_{Emissions}$ = Emissions index

And:

$$I_{Emissions} = 1 - \frac{(\text{actual value} - \text{min. target value})}{(\text{max. target value} - \text{min. target value})} = \frac{\text{max} - \text{actual value}}{\text{max} - \text{min}}$$

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[72] Max is computed as the highest observed values in the 1980–2012 period and min refers to somewhat arbitrarily defined "subsistence values" equal or below the minimum observed values: 20 years of life expectancy, zero years of schooling and 100 PPP Dollars of income in the 2013 report (UNDP, 2013).

The Happy Planet Index (HPI):

Introduced in 2006 by the New Economics Foundation (NEF), the HPI is a measure of a country's ecological efficiency in delivering human wellbeing.[73] It is a composite of two objective indicators (Life expectancy and Ecological footprint) and one subjective indicator ('life satisfaction' built up from Experienced wellbeing) measured by surveys. Multiplying longevity and the subjective life satisfaction, you get the 'degree to which people live long and happily in a certain country at a given time', also called Happy Life Years (HLY) (SHEPELMANN *et al*., 2010; ABDALLAH *et al*., 2012). The HPI is calculated as follows:

$$\mathbf{HPI} = \frac{\text{Experienced wellbeing x Life expectancy}}{\text{Ecological footprint}}$$

Some adjustments are made to ensure that all three components have equal variance so that no single component dominates the overall index (ABDALLAH *et al*., 2012). The third and last HPI report (ABDALLAH *et al*., 2012) covers 151 countries. Nations score well when they achieve high levels of satisfaction and health while impacting environmental resources lightly. No country is able to combine success across the three goals of high life expectancy, high experienced wellbeing and living within environmental limits.

3.4.2. Aggregate indicators using the *adjusting* GDP approach: GPI, IEWB, SSI, and IWI

Those indicators that use the *adjusting approach* would typically begin with a key component of GDP like personal consumption data or the GDP itself, then adjust it to reflect the social costs of inequality and diminishing returns to income received by the wealthy, add a variety of monetized environmental and social factors (e.g. housework, parenting, volunteering and high education), and deduct costs associated with pollution, loss of leisure time, crime, automobile accidents as well as costs that reflect the undesirable and/or deleterious side effects of economic progress (e.g.

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[73] More detailed information on HPI can be found on the NEF website: http://www.happyplanetindex.org.

destruction or degradation of natural capital and international debt). Advocates of the use of indicators that use this approach argue that it is rather straightforward to revise already existing accounting protocols (JACKSON AND MCBRIDE, 2005; COSTANZA *et al*., 2009).

Examples of *adjusting* GDP indicators include the Index of Sustainable Economic Welfare (ISEW) and its successor, the Genuine Progress Indicator (GPI) (ANIELSKI AND ROWE, 1999, TALBERTH *et al*., 2007, and KUBISZEWSKI *et al*., 2013), the Index of Economic Wellbeing (IEWB) (OSBERG AND SHARPE, 1998 and 2011), the Sustainable Society Indicator (SSI) (VAN DE KERK AND MANUEL, 2009 and 2014), and the Inclusive Wealth Indicator (IWI), as follows:

Index of Sustainable Economic Welfare (ISEW)/Genuine Progress Indicator (GPI):

The Index of Sustainable Economic Welfare (ISEW), later revised and renamed the Genuine Progress Indicator (GPI), was first developed for the United States for the years 1950 and 1988 by Herman Daly and John Cobb in 1989 (DALY AND COBB, 1989). The ISEW follows the *adjusting* GDP approach as it starts out from the same personal consumption data used in GDP, then makes several adjustments to account for inequalities in the distribution of incomes, non-monetized contributions to welfare from services provided by household labor (the ‘informal economy’), environmental costs arising from certain types of air and water pollution, as well as noise pollution and climate change, certain expenditures such as private expenditures on health, education, commuting, car accidents and personal pollution control, changes in the sustainability of the capital base (JACKSON *et al*., 2005; COSTANZA *et al*., 2009). Taken together all adjustments made are reflected as follows:

ISEW = Personal consumer expenditure
– adjustment for income inequality
+ services from domestic labor
– costs of environmental degradation
– defensive private expenditures
+ non-defensive public expenditures
+ economic adjustments
– depreciation of natural capital

Since the publication of the original study on the ISEW for the United States, several similar studies have been carried out (see JACKSON AND MCBRIDE, 2005). In 1995, Clifford Cobb[74] developed the Genuine Progress Indicator (GPI) based on the same methodology as ISEW (GOOSSENS *et al*., 2007) and thus also following the *adjusting* GDP approach. Derived from 26 separate time series data spanning the period 1950-2004 (TALBERTH *et al*., 2007), GPI adds a number of new categories such as the value of household and volunteer work and subtracts factors such as costs of crime and family breakdown, loss of leisure time, cost of underemployment and cost of resource depletion (GOOSSENS *et al*., 2007). It is calculated as follows:

GPI = personal/household consumption expenditures
\+ value of household work not counted in GDP
\+ value of volunteer contribution work
– crime factor
– environmental degradation factor (resource depletion, ozone depletion, pollution, etc.)
– family breakdown factor
– overextended worker stress factor
– exploding consumer debt
– inequality of distribution of wealth and income

The Index of Economic Wellbeing (IEWB):

In 1998 the Centre for the Study of Living Standards (CSLS) developed the Index of Economic Wellbeing (IEWB), a composite index based on a conceptual framework for measuring economic wellbeing developed by Lars Osberg for the MacDonald Commission in 1985.[75] The IEWB follows the *adjusting* GDP approach, measuring the contribution of a country's economy to the overall level of wellbeing enjoyed by its citizens in four domains of economic welfare: per capita consumption, per capita wealth, economic equality and economic security, as follows (OSBERG AND SHARPE, 2011):

IEWB = consumption flow
\+ wealth stocks
\+ equality
\+ economic security

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[74] Senior Fellow of the think-tank Redefining Progress (http://rprogress.org).

[75] More detailed information on IEWB can be found on CSLS website: http://www.csls.ca/iwb.asp .

These four domains reflect economic wellbeing in both the present and the future, and account for both average access to economic resources and the distribution of that access among members of society (OSBERG AND SHARPE, 2011). Each domain, in turn, comprises 18 indicators and their aggregation can be done based on equal weights or as best perceived by the user.

The Sustainable Society Indicator (SSI):

First launched in 2006 and last updated in 2016, the Sustainable Society Index (SSI) also follows the *adjusting* GDP approach. The framework of the SSI includes twenty-one indicators clustered first into seven sub-dimensions and, then, into three dimensions of wellbeing: Human Wellbeing (HW), Environmental Wellbeing (EW) and Economic Wellbeing (EcW); calculated as follows (VAN DE KERK AND MANUEL, 2014):

$\mathbf{SSI_{HW}}$ = basic needs + health + personal and social development
$\mathbf{SSI_{EW}}$ = natural resources + climate and energy
$\mathbf{SSI_{EcW}}$ = transition + economy

SSI has been calculated for 154 countries, looking at years 2006, 2008, 2010, 2012, 2014 and 2016. Results from 2006 and 2016 indicate that the world has become a little more sustainable in terms of economic and human wellbeing, in contrast to a small decline in environmental wellbeing over the same period (SSF, 2017).[76]

The Inclusive Wealth Index (IWI):

The IWI is a joint initiative of the United Nations University-International Human Dimensions Programme (UNU-IHDP) and the United Nations Environmental Programme (UNEP) in collaboration with the United Nations Educational, Scientific and Cultural Organization (UNESCO) that was first launched during the 2012 United

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[76] More detailed information on SSI can be found on the Sustainable Society Foundation website: http://www.ssfindex.com.

Nations Conference on Sustainable Development. The IWI was conceived primarily to help countries assess changes in capital stocks of three key assets (human capital, produced capital, and natural capital) deemed critical to ensure long-term sustainability (UNU-IHDP AND UNEP, 2014).[77] It adopts the *adjusting* GDP approach. It seeks to measure the social value of capital assets of nations by going beyond the traditional economic concept of manufactured (or produced) capital (e.g. machinery, buildings, infrastructure).[78] As such, the IWI claims to be "inclusive" in the sense that it also accounts for other important components of the productive base of the economy, such as natural capital (e.g. land, forests, fossil fuels and minerals) and human capital (the population's education and skills). The framework is based on the capital approach to sustainability and, as such, it expresses intergenerational wellbeing as a function of capital assets and time.[79] After estimating major wealth components separately,[80] they are aggregated into a weighted average using shadow prices (MUÑOZ *et al.*, 2014), as follows:

$$\begin{aligned}\textbf{IWI} \; &= P_{pc} \text{ x produced capital}\\ &\quad P_{hc} \text{ x human capital}\\ &\quad P_{nc} \text{ x natural capital}\end{aligned}$$

where P′s are shadow prices

The shadow prices used are also meant to represent the marginal contribution of each capital to the overall intergenerational well-being at each point in time. The last Inclusive Wealth Report (UNU-IHDP AND UNEP, 2014) presents estimates of inclusive wealth for five-yearly intervals changes from 1990 to 2010 for a group of 140 countries, which together represent 95 percent of the world population and 99 percent of world GDP.

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[77] More information about the IWI can be found in the IHDP website: http://www.ihdp.unu.edu.

[78] The conceptual framework behind the IWI is provided in ARROW *et al.* (2012).

[79] According to THIRY AND ROMAN (2014), this approach relies upon a fragile theoretical construct, namely the "equivalence theorem" that is "neither theoretically justified nor empirically grounded".

[80] Produced capital is calculated according to the perpetual inventory method (PIM), starting from an initial estimate. Human capital is calculated based on a function of educational attainment and life-long returns on education, using a methodology proposed in KLENOW AND RODRIGUEZ-CLARE (1997) (UNU-IHDP and UNEP, 2014). Natural capital is computed based on the physical amount of each asset type and corresponding resource rent.

3.4.3. Aggregate indicators using the *supplementing* GDP approach: SPI

Those that use a *supplementing approach* are independent of GDP and are meant to complement it with additional environmental and/or social data. They are also known as ‘Beyond GDP indicators’ (WHITBY *et al.*, 2014). Advocates of the use of measures that supplement GDP point out that GDP, while a poor measure of welfare, nonetheless “serves crucial and helpful roles in macroeconomic policy” and is “unique in that it combines simplicity, linearity, and universality as well as carries the objectivity of the observable market price as its guiding principle” (GOOSSENS *et al.*, 2007).

A well-known example of an aggregate indicator that uses the supplementing approach is the Social Progress Index (SPI) (PORTER *et al.*, 2016).

The Social Progress Index (SPI):

Launched in April 2013, the Social Progress Index (SPI) is the latest alternative indicator developed. SPI measures the extent to which countries provide for the social and environmental needs of their citizens. The initiative came out of a working group of the World Economic Forum, aiming at interpreting progress differently, influenced by the writings of Amartya Sen, Douglass North, and Joseph Stiglitz (BISHOP, 2013). It comprises 52 indicators in the areas of basic human needs, foundations of wellbeing, and opportunity, each of which are broken down further into four categories (PAULSON, 2013). The overall index is calculated as the unweighted sum of the three dimensions (PORTER *et al.*, 2016), as follows:

$$\mathbf{SPI} = \tfrac{1}{3}\Sigma\ [\tfrac{1}{4}_{k}\,\Sigma\ \text{Component}_{k}]$$

Dimension 1: basic human needs
Dimension 2: foundations of wellbeing
Dimension 3: opportunity

The SPI follows the *supplementing* GDP approach and distinguishes itself from previous efforts to measure wellbeing in the sense that it is based exclusively on non-economic indicators and on outcome indicators, it integrates a large number of indicators that are relevant for all income levels, and its model allows empirical investigation of relationships between dimensions, components and indicators. It has been initially calculated for fifty countries in 2012 and most recently for one hundred and thirty three countries in 2016 (PORTER *et al.*, 2016).[81]

3.4.4. Barriers to the deployment of new measurements

Similar to GDP, alternative indicators can only provide a bird's eye view of how a society is doing. Nonetheless, some of the alternative indicators listed above can be useful for policy analysis in the sense that it is possible to use and compare their results on an international scale (in particular HDI, SSI, and HPI). In fact, some have been used to inform local and regional communities (e.g. GPI, ISEW). As noted by COSTANZA *et al*. (2009), this fact alone can be seen as an improvement to the misuse of GDP as a proxy for wellbeing.

However, none of the existing alternative indicators seem to have gained enough public perception and political support to be able to challenge the hegemony of GDP as a single indicator of a country's wellbeing. Moreover, despite the extensive literature criticizing the use of GDP per capita as a measure of wellbeing and a growing literature proposing corrections and alternative indicators, the influence of GDP information on the economy and policy- and decision-making has by no means declined (VAN DER BERGH, 2009). This is possibly due to the less objective and tangible nature of sustainability aspects such as quality of life and ecological integrity and to the complex and multidimensional nature of such alternative indicators. Methodological limitations and shortcomings could also be a reason for their inability to gain broad acceptability.

There are, in fact, significant barriers preventing the development, implementation and widespread use of alternative indicators to GDP (COSTANZA *et al.*, 2009; WHITBY *et al.*, 2014). The existing barriers can be generally categorized as technical, political, or institutional, as discussed next.

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[81] More information about the SPI can be found in the Social Progress Imperative website: http://www.socialprogressimperative.org.

Technical barriers:

The absence of a strong theoretical foundation around human wellbeing leads to inevitable disagreements on how best to quantify it, as well as to numerous technical questions around the methodologies used to develop existing alternative indicators. Technical barriers discussed in the literature involve issues related to data (e.g. availability, access, reliability) or to methodology (e.g. valuation, standardization).

Data issues

The data-related issues involve primarily availability and reliability of the underlying data. Availability relates to the timeliness and the scale and scope of the data collected. Data scope, availability, timeliness and/or reliability are critical for the creation and use of alternative indicators to GDP. To be useful, an indicator needs to be reliable and the underlying data needs to be available in a timely fashion and at an appropriate scale and scope (COSTANZA *et al*., 2009).

Lack of internationally comparable data poses significant limitation to the widespread use of any alternative indicator to GDP. Data availability can differ significantly from country to country and data reliability has been a constant challenge in many developing countries. That is very likely the reason the majority of the existing alternative indicators have only covered OECD countries, which already have reliable data collection systems in place. Some of the few alternative indicators that do provide data for comprehensive worldwide assessments have resorted to interpolations to address lack of data over a full period in certain countries (KUBISZEWSKI *et al*., 2013; OSBERG AND SHARPE, 2011; TALBERTH *et al*., 2007; UNU-IHDP AND UNEP, 2012 and 2014). Moreover, lack of data availability has led to the exclusion of key elements, for instance fish stocks and subsoil water from ANS (WORLD BANK, 2006). Data limitations in certain countries have also led to the omission of certain natural resource categories like groundwater, fisheries and minerals, as well as of social capital altogether in the computation of the IWI (UNU-IHDP and UNEP, 2012).

Finally, for an indicator to be deemed reliable, it must meet certain standards of accuracy and timeliness that existing environmental and social data may not provide (COSTANZA *et al.*, 2009). There is clearly a need for better data availability on multiple aspects of social and environmental conditions. Overcoming these data-related barriers will likely require allocation of the necessary financial resources to complete, improve and maintain existing data collection systems, as well as to build new ones in certain cases (WHITBY *et al.*, 2014).

Methodology issues

The methodology-related issues involve questions around the values implied or standardization concerns (COSTANZA *et al.*, 2009). Criteria selection and valuation methods used in some of the alternative indicators presented above (e.g. IEWB, GPI) have been questioned in terms of arbitrariness and lack of robustness (e.g. LAWN, 2005; DA VEIGA, 2010). Because of their inherent complexity, methodologies used to convert environmental and social indicators into monetary variables, e.g. for estimating the damage costs of CO_2 emissions, receive strong criticisms (GOOSSENS *et al.*, 2007).

The choice of indicators of societal wellbeing, as well as the indicators themselves should reflect societal choices, values, and goals (COSTANZA *et al.*, 2009). The concept of value has its roots in utilitarianism, as discussed in section 3.2.1. As such, economic valuation entails the assessment of the degree to which a good or service satisfies individual preferences in terms of the amount of money (the utilitarian "measurement stick") an individual is willing to pay for a good or service or to accept as a compensation for forgoing the good or service. Willingness to pay (WTP) and willingness to accept (WTA) are value measures based on the assumption of substitutability in preferences that adopt different reference points for levels of wellbeing, absence and presence of improvements, respectively (FREEMAN, 2003).

Many goods and services are exchanged on a market, which automatically reveals their direct value. For some natural resources, their value is almost exclusively related to their direct use (e.g. crude oil). We are willing to pay for it only as much as the energy it creates is worth to us. Many other natural resources also highly valued for their direct use, may however have several other uses, which comprise their overall worth (e.g. lakes, oceans and rivers). Hence, many goods and services, especially environmental ones, may be valued for reasons related to indirect use, usually related to special functions of some ecosystems (COSTANZA *et al*., 1997; Daly 1997a; Daly *et al*., 2000; DE GROOT *et al*., 2002).

Moreover, goods and services may also be valued for their potential to be available in the future, which constitute an option value. It may be thought of as an insurance premium one may be willing to pay to ensure the supply of the environmental good later in time.[82] There is no consensus even among environmental economists as to the exact placement of option value among use and non-use components of total economic value. It is however known that it can only be calculated if there is enough information on preferences to calculate both option price and expected surplus. Key components of these alternative indicators end up with limited validity due to the inexistence of proper information on preferences. Even with those based on market prices (IWI's resource depletion is valued as 'market prices minus costs of production', for instance) the results depend strongly on the various factors affecting market prices, limiting the validity of the results yielded.

Furthermore, many forms of capital are not traded in markets and thus there is no market price at which to value these assets (UNU-IHDP and UNEP, 2012). Several non-market valuation methods have been devised for direct and/or indirect use (e.g. hedonic price), as well as option values (e.g. stated preference) of ecosystem goods and services (UNU-IHDP and UNEP 2012). Table 1 below lists various non-market methods that can be used for valuing ecosystem goods and services. Their application is limited due to measurement issues, data availability and other limitations. Therefore, economists, ecologists and other natural scientist face fundamental challenges in trying to apply environmental valuation methodologies to non-market ecosystem services.

In order to incorporate non-market good and services, some alternative indicators resort to surveys and other subjective data collection approaches. The lack of standardization and the subjective nature of the decisions taken in the development process of indicators (i.e. the use of "explicit or implicit value judgments" as noted in

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[82] The concept of option value was first introduced by Weisbrod in 1964 (FREEMAN, 2003).

Kuznets 1962) are strongly criticized (NEUMAYER, 2004; LAWN, 2005).

Table 1 - Selected non-market valuation methods applied to ecosystem services.

Valuation method*		
	avoided; existence and bequest values of preserving ecosystems	All of the above

Source: UNU-IHDP and UNEP 2012.

Methodology standardization refers to the decisions underlying the construction of an indicator—which items are chosen, how items are measured, and how different items are combined (COSTANZA *et al*., 2009). Given the different approaches and methodologies used and the lack of a consensus on standards, comparability among indicators is remarkably low. The lack of a common standard is partially a result of the divergent and contrasting nature of underlying concepts (e.g. quality of life, living standards, human development and sustainable development) and terminology (e.g. wellbeing and sustainability) across the different actors involved (WHITBY *et al*., 2014), as discussed in section 3.2.2. As mentioned previously, an unprecedented massive effort will likely be needed to integrate the existing conceptual approaches into a coherent theory of wellbeing (CARPENTER *et al*., 2009).

Furthermore, some authors have questioned the possibility and merit of quantifying sustainability factors in a single, monetary unit (DA VEIGA, 2010; GOOSSENS *et al.*, 2007). Aggregation into one single indicator assumes perfect substitutability, implying that additional benefits from a growing stock of one type of capital (e.g. man-made, natural, intangible) can perfectly substitute the reduced benefits arising from a diminished stock of another type of capital. It can also divert attention from single sustainability challenges by masking complex socio-economic and ecological interlinkages (SCHEPELMANN *et al.*, 2010).

Political barriers:

Political barriers to a broader dissemination of alternative indicators to GDP include lack of democratic legitimacy (WHITBY *et al.*, 2014), and lack of political leadership (CONSTANZA *et al.*, 2009).

The general public has not endorsed alternative indicators to GDP (WHITBY *et al.*, 2014). GDP, by contrast, has arguably received public endorsement as both a key driver of and a proxy measure for societal development and wellbeing. This lack of legitimacy results in part from the fact that alternative indicators to GDP are not underpinned by a coherent, politically compelling narrative to compete with the orthodox narrative that underpins GDP: i.e. that markets will deliver optimal outcomes except where specific market failures are identified, and that maximizing growth while correcting market failures will therefore maximize societal development and wellbeing (WHITBY *et al.*, 2014). Without democratic legitimacy and a strong, compelling narrative that can circumvent the pressures created by the economic crisis, there cannot be a strong demand from electors for politicians to prioritize the development and widespread use of alternative indicators to GDP.

Furthermore, there is lack of political leadership on the widespread use of alternative indicators to GDP in view of the uncertainty around the impact they can have on the performance of existing policies. If new indicators show that past and current policies create problems, they will reflect badly on the people in charge of making those policies (COSTANZA *et al.*, 2009). One of the most publicized examples of this is China’s recent attempt to develop a Green GDP. Announced in 2004, the Green GDP project was canceled in 2007 because of political concerns, in part due to how the results reflected on the performance of specific regions (TALBERTH, 2008).

Institutional barriers:

Reported institutional barriers to a broader dissemination of alternative indicators to GDP include the dominance of the “growth is good” paradigm, the interest in maintaining the status quo, and the lack of a clear process for integrated and innovative economic policy making (COSTANZA *et al*., 2009; WHITBY *et al*., 2014). According to COSTANZA *et al*. (2009). These barriers are primarily based on resistance to change.

The belief that economic growth ultimately solves all problems is perhaps the most difficult barrier to alternative measures of progress (COSTANZA *et al*., 2009) and, thus, to the widespread use of existing alternative indicators to GDP. While economic growth may provide choices, by itself, it offers no guarantee of increased wellbeing (O’DONNELL *et al*., 2014). Many established organizations and institutions have a vested interest in maintaining the status quo (COSTANZA *et al*., 2009). WHITBY *et al.* (2014) came across clear resistance to abandoning traditional objectives and the informal models that support them. This resistance is effective to the extent that (a) there is no political imperative for change and (b) the existing structures and processes preserve the power of those resisting. There has been relatively little development of models linking policy with overall wellbeing, in contrast to the well-established formal models that guide the development of economic policy designed to maximize economic growth and market efficiency. Innovative policy making processes are needed.

In spite of the barriers discussed above, taken together, the existing alternative indicators offer the building blocks for something more adequate than GDP (COSTANZA, 2014; STIGLITZ *et al*., 2009). Most of them, in particular when applied to more developed countries, have evolved more or less in line with GDP until about the mid-1970s and early 1980s, at which point they tend to stabilize or decline, in spite of continued growth in GDP (JACKSON AND MCBRIDE, 2005; ROY *et al*., 2012; KUBISZEWSKI *et al*., 2013). For instance, the U.S. GPI has peaked in the late 1970s and stagnated ever since while the U.S. economy has grown steadily since 1950

(TALBERTH *et al.*, 2007). Also, IEWB estimates for 14 OECD countries for the period 1980-2009 show that economic wellbeing has not advanced as rapidly as GDP per capita (OSBERG AND SHARPE, 2011).

These results bring forward a consensus around the existence of a threshold level, beyond which economic growth no longer adds to collective wellbeing (DALY, 1977 and 1996; DIETZ *et al.*, 2009 and 2012; JORGENSON AND DIETZ, 2015; PORTER *et al.,* 2016). Compared to GDP, HPI rises sharply as GDP rises, with a peak at a per capita GDP ($PPP) of 5,000 USD and declines afterwards further and further as GDP increases (MARKS *et al.*, 2006). When contrasted to GDP per capita, SPI revealed that as countries become wealthier, they also become increasingly less sustainable from an environmental and natural resource perspective (PAULSON, 2013; PORTER *et al.*, 2016).

This threshold phenomenon is also consistent with the saturation and decoupling effects between energy consumption and human development measured in terms of HDI well examined in the literature, as discussed in section 2.4.2 above. This phenomenon clearly shows the need for countries to shift from economic growth towards sustainable development goals, as well as the need for deployment of new measures of collective wellbeing (IIASA, 2012).

4. Bridging the energy divide: a quantitative assessment

As discussed in chapter 2, at current decarbonisation rates and state of knowledge and technology, the additional energy needed to bridge the current energy divide and, thereby, enable the achievement of higher levels of collective wellbeing, only adds to the already daunting challenge of securing climate stabilization.

Although the linkages between energy use and human development and wellbeing have been object of increased empirical research, as shown in section 2.4, there has been no study that assesses the energy needs associated with higher levels of collective human wellbeing, using a measure of the latter that aims to monitor progress towards sustainable human development and, as such, encompasses all three dimensions of sustainable development within a single value.

This study aims to overcome this shortcoming by selecting a potential proxy for human wellbeing from the alternative indicators to GDP and providing an indication of whether meeting the urgent energy needs while enabling the achievement of higher levels of collective wellbeing would be consistent or conflict with climate stabilization efforts, while trying to answer the following four pressing questions:

1. How much energy consumption, and its corresponding CO_2 emissions, would be needed to bridge the energy divide and enable the achievement of higher levels of collective wellbeing?

2. Would existing carbon budgets associated with climate stabilization be affected?

3. If so, what part(s) of the world would be mostly at risk? And

4. What needs to be done to bridge the energy divide and increase wellbeing while staying within existing carbon budgets?

In order to accomplish this, a quantitative assessment framework has been devised as presented in this chapter. The first step (section 4.1) involves the selection of the most appropriate proxy for human wellbeing from the key alternative indicators to GDP discussed in section 3.4 (also listed in Appendix B). The second step (section 4.2) deals with data preparation, e.g. data collection, regional aggregation of countries, and analysis of the dataset to identify trends in regional levels of human wellbeing and rates of change overtime. Next (section 4.3), aggregate levels of wellbeing are projected into 2050. In the fourth step (section 4.4), the relationship between the selected indicator and energy consumption is described mathematically, such that correlations over different years reveal (through elasticities) how human wellbeing has responded to changes in energy consumption over time in each region.

The fifth step covers the actual quantitative exercise (section 4.5), whereby a range of primary energy consumption rates (on a per capita basis) needed to achieve higher collective wellbeing are estimated using future wellbeing elasticities of energy consumption projected based on the historical elasticities obtained in the previous step. The overall annual energy consumption levels are then obtained using population projections from the IAM Model for Energy Supply Systems Alternatives and their General Environmental Impact (MESSAGE v.4) used in the LIMITS project (KRIEGLER *et al*., 2013, TAVONI *et al*., 2013 and 2014), which is included in IPCC's AR5 Scenario Database (IAMC AR5 Scenario Database, 2014).[83] The associated carbon impact is then estimated by applying CO_2 emission intensities from the no-policy baseline scenario of the IAM MESSAGE to the projected overall annual energy consumption levels.

The IAM MESSAGE is a leading multi-regional systems engineering optimization model with considerable technology detail of the global energy system used for energy system planning and policy analysis. It deploys technology-specific assumptions on availability, performance, and costs of energy conversion technologies whose dynamics unfold over time (RIAHI *et al*., 2007).

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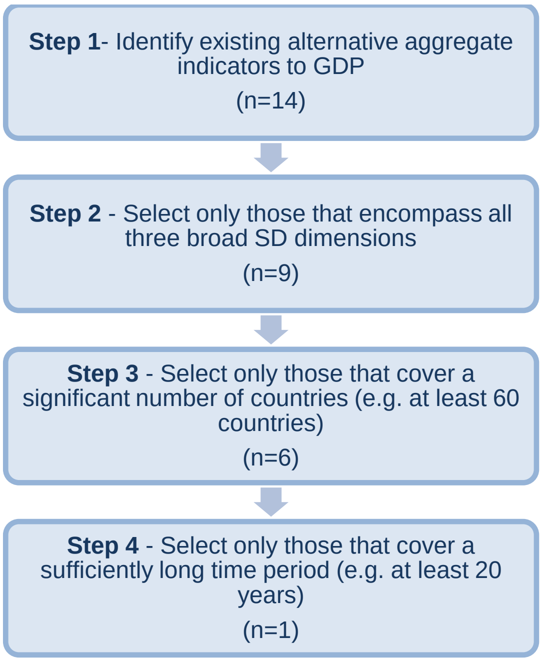
[83] As noted in section 2.3.2, the LIMITS project is one of several multi-model analytical studies that exploit the potential range of emissions pathways consistent with meeting the 2 ºC target (KRIEGLER *et al*., 2013). Further information on this project can be obtained in the project website (http://www.feem-project.net/limits/).

Consistent data sets were used throughout the analysis. Unless otherwise mentioned, historical data used in the analysis were obtained from the World Development Indicators (WORLD BANK, 2016). All data from the IAM MESSAGE v.4 were obtained from the LIMITS Scenario Database (LIMITS Database 2016) and confirmed in IPCC's AR5 Scenario Database (IAMC AR5 Scenario Database, 2014). Key data and assumptions used in the analysis are summarized in Appendix C.

4.1. Selecting proxies for human wellbeing from alternative indicators to GDP

This section presents the first step of the quantitative assessment framework: the selection of the appropriate proxy(ies) for human wellbeing from the existing alternative indicators to GDP examined in section 3.4 above (also listed in Appendix B).

As discussed in section 3.4, a number of new ways to measure societal wellbeing have come forward in response to the growing criticisms to the use of GDP as a proxy for national wellbeing, including a number of new aggregate indicators conceived to either replace, adjust, or supplement GDP. Figure 12 illustrates the selection process used.



Note: SD = sustainable development, n = number of indicators

Figure 12 - Selection process for the appropriate proxy(ies) for human wellbeing.

The first requirement to identify potential proxies to human wellbeing among the existing alternative indicators to GDP involves selecting those that encompass all three broad sustainable development dimensions, namely: economic growth, social and/or human development, and environmental protection. After applying this first criterion, only 9 of the original 14 alternative indicators examined and listed in Appendix B remain as potential proxies.

In order to ensure a robust quantitative analysis and obtain broad trends it is essential to have data across a relevant number of countries and over a sufficiently long time period. As such, we then examine whether and which of the 9 potential proxy indicators cover over sixty countries (including both industrialized and developing countries) and span over at least twenty years.[84] When these last criteria are applied only one alternative indicator passes muster, the Inclusive Wealth Indicator (IWI). Section 3.4.2 provides detailed information about this indicator.

It is noteworthy that five other indicators have data encompassing over sixty countries, however, they fail to provide data over the required time period of at least twenty years. The Sustainable Society Index (SSI) would be the closest one to meet this criterion, with data from 2006 through 2016. However, even if there were data available on energy consumption for all the years in this time period, the use of this indicator would yield only 11 years of useful data (2006 through 2016, inclusive), which would not be sufficiently long to yield robust trends needed for the analysis. Moreover, the SSI presents data in three different broad dimensions without actually aggregating them into a single indicator.

Even though the IWI was selected as proxy for wellbeing that encompasses all three broad sustainable development dimensions, it is important to acknowledge that the IWI encompasses only some aspects of each dimension. For example, human capital does not consider average life expectancy or any other health-related aspect for that matter.[85] Similarly, the atmospheric commons is not considered among the natural

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[84] The OECD requires twenty years of data to model econometric relationships (WHITBY *et al.*, 2014).

[85] Even though deemed relevant by the IWI proponents, health components were not included in the final calculation of the IWI in view of unresolved normative issues about the role of health (ARROW *et al.*,

assets in the IWI composition.[86]

Another important limitation worth of note results from the production-based accounting of natural resource depletion. As such, a given country's IWI could be understating or overstating the value of resources required domestically based on resources flow in international trade interactions.[87] In addition, IWI's heavy reliance on shadow prices has been criticized in the literature. According to SOLOW (2013) and THIRY AND ROMAN (2014) shadow prices cannot capture the degree of substitution across the different forms of capital, reflect the contribution to intergenerational well-being at each time-period by each capital asset, reflect future scarcities, or capture all the externalities that might have been caused in the production process. Moreover, data availability can be a challenge and thereby affect the valuation of certain capital components, as noted in ROMAN AND THIRY (2016) and LANDERRETCHE *et al.* (2017) for natural capital.

4.2. Data preparation and analysis

4.2.1. Data collection

IWI data used in this analysis were obtained from the Inclusive Wealth Report 2014 (UNU-IHDP and UNEP 2014) and cover a group of one hundred and forty countries, spanning from 1990 to 2010. Per capita values were calculated by using population data from the World Development Indicators (WORLD BANK, 2016).

After eliminating countries for which no data on energy consumption were available throughout the selected period (1990-2010), the IWI country sample was

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2012).

[86] The IWI proponents have further calculated an adjusted IWI that deducts carbon damage caused by carbon emissions into the atmosphere. However, the carbon-adjusted version of the IWI is not used in the present analysis.

[87] The proponents of the IWI have provided a valuation analysis of natural assets in international trade that provide relevant insights into identifying the drivers of natural capital change and where there could be over- or understatements of the value of resources actually needed by domestic (open) economies for which the IWI was calculated. While resources tend to flow from poor to rich countries, there is no steadfast rule regarding the relationship between income and production or consumption driven depletions (UNU-IHDP AND UNEP, 2012). As such, even though, in general, production entails greater resource depletion than consumption in lower-income, resource-rich economies, it is not exclusively the case (e.g. India, Nicaragua, and Eastern Europe) (UNU-IHDP AND UNEP, 2012).

reduced to one hundred and eighteen countries, which together represent 93 percent of the global population, 91 percent of the global CO_2 emissions, and 96 percent of the global GDP (PPP) and of the global primary energy consumption, based on 2010 data from the World Development Indicators (WORLD BANK, 2016).

Energy consumption is calculated based on per capita energy use data obtained from the World Bank's World Development Indicators (WORLD BANK, 2016). It refers to the use of primary energy before transformation to other end-use fuels (i.e. indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport) measured in kilograms of oil equivalent (koe) per capita converted to billion Joules (GJ) using IEA's energy unit converter (OECD/IEA 2016).

4.2.2. Regional aggregation

In order to estimate the potential carbon impact of further advancement in human wellbeing, we combine the selected countries into a set of five macro-regions referred to as Region Categorization 5 (RC5), following the aggregation used in IPCC's GHG concentrations pathways extending up to 2100, for which all relevant IAMs produced corresponding emission scenarios (CLARKE *et al.*, 2014; IAMC AR5 Scenario Database, 2014; KREY *et al.*, 2014).[88]

As such, the one hundred and eighteen countries for which data on IWI and energy consumption from 1990 through 2010 exist are organized into the RC5 regions, namely: OECD 90 countries (OECD90) - countries that were members of the Organisation for Economic Co-operation and Development **(**OECD) in 1990-, Economies in Transition (EIT) – countries from the Reforming Economies of Eastern Europe and the Former Soviet Union, Asia (ASIA) - most Asian countries with the exception of the Middle East, Japan and Former Soviet Union states, Middle East and Africa (MAF) - countries of the Middle East and Africa, and Latin America (LAM) - countries of Latin America and the Caribbean. Appendix D provides a complete list of countries covered in each region.

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[88] This five-region level was also used in IPCC's so-called Representative Concentration Pathways (RCPs) (IAMC AR5 Scenario Database, 2014; CLARKE *et al.*, 2014).

4.2.3. Dataset analysis

We then analyze the dataset to identify important trends. Table 2 below reports population-weighted averages for the two variables IWI and EC, overall and broken down by region. According to the IWI data there has been a small improvement in human wellbeing, i.e. the average per capita IWI for our sample of one hundred and eighteen countries has increased by approximately 6 percent over the full period (1990-2010).

Table 2 - Key data values by year and region.

Series and regions	**1990**	**1995**	**2000**	**2005**	**2010**	**Growth in the period 1990-2010**
***pcIWI*-All**	87,652	87,327	88,166	90,526	92,602	6%
***pcIWI*-ASIA**	16,248	16,800	17,613	18,669	20,779	28%
***pcIWI*-EIT**	94,271	95,904	98,576	101,934	104,831	11%
***pcIWI*-LAM**	74,931	73,975	73,869	74,458	75,944	1%
***pcIWI*-MAF**	49,724	46,786	43,913	42,340	41,956	-16%
***pcIWI*-OECD90**	346,140	357,117	372,801	392,867	405,396	17%
***pcEC*-All**	70	68	69	75	79	14%
***pcEC*-ASIA**	24	28	30	38	49	104%
***pcEC*-EIT**	188	138	129	141	149	-21%
***pcEC*-LAM**	44	45	47	51	56	27%
***pcEC*-MAF**	39	43	44	50	54	40%
***pcEC*-OECD90**	200	206	216	216	201	1%

Notes: Population-weighted averages by year and region. *pcIWI* = per capita Inclusive Wealth Index (in 2005 US$), *pcEC* = per capita Energy Use (in koe). Decrease in *pcEC* in EIT between 1990 and 2000 reflect the deep recession that took place in the region after the collapse of the Soviet era.

Source: Prepared by the author based on data from UNU-IHDP and UNEP (2014) for IWI and the WORLD BANK (2016) for population and *pcEC*.

While somewhat encouraging, a closer look reveals that the improvement has been quite uneven, per capita IWI has gone up by about 28 percent in ASIA, 17 percent in OECD90, and 11 percent in EIT, whereas in LAM there was a increase of only 1 percent, while in MAF there was actually a decrease of 16 percent. The latter contrasts strongly with the region's performance in term of human development measured in HDI. The average improvement in HDI in the region was 19 percent over the same period.[89] Figure 13 shows how the two variables have evolved for the overall sample of one hundred and eighteen countries since 1990, compared to GDP and to HDI.

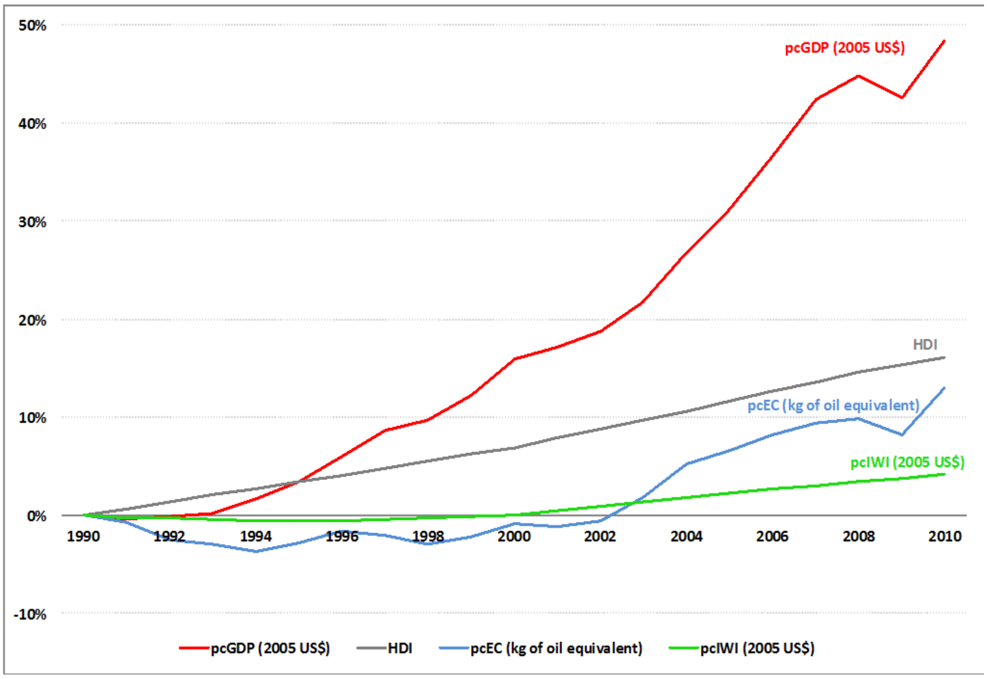

Figure 13 - Observed changes in energy consumption measured in per capita primary energy consumption (*pcEC*), in wellbeing measured in per capita IWI (*pcIWI*), in income measured in per capita GDP (*pcGDP*) and in HDI for the overall sample between 1990 and 2010.

Sources: UNU-IHDP and UNEP (2014) for IWI, the WORLD BANK (2016) for population, *pcEC*, and *pcGDP*, and UNDP (2013) for HDI.

Meanwhile, when taking energy consumption data into consideration, it is noteworthy to highlight that the average per capita energy consumption level in ASIA increased by more than 100 percent over the same period, while in the OECD countries the average increased by only 1 percent. This shows how energy intensive development in Asia has been in the period. Similarly, despite an increase of 40 percent in its average

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[89] Calculated based on data from UNDP (2013).

per capita energy consumption, MAF was not able to see any improvement in its wellbeing.

4.3. Projecting aggregate levels of human wellbeing into 2050

Next, we project the aggregate levels of human wellbeing measured in per capita IWI (*pcIWI*) forward to 2030 and 2050 based on rates of change in human wellbeing over time (*r*) and estimated population growth (*projectedPop*) from the IAM MESSAGE (v.4) used in the LIMITS project (KRIEGLER *et al*., 2013, TAVONI *et al*., 2013 and 2014), as follows:

$$\boldsymbol{Projected\,pcIWI_j} = \left(\frac{(\boldsymbol{IWI_{t-1}} \times (\mathbf{1} + \boldsymbol{r_k}))}{\boldsymbol{projectedPop_j}}\right)$$

Three sets of growth rates (*r*) were used for each region. The average compound annual growth rate between 2005 and 2010 was used to project increases in well-being for the years 2011 through 2020. The average between 2000 and 2010 was used for the years 2021 through 2030. And the average between the whole observed time period (1990-2010) was used for the remaining years. Projected population levels were calibrated to the start of the projection period.

All data from the IAM MESSAGE v.4 were obtained from the LIMITS Scenario Database (LIMITS Database, 2016) and confirmed in IPCC’s AR5 Scenario Database (IAMC AR5 Scenario Database, 2014). Projected levels of wellbeing across all regions for years 2030 and 2050 are shown in Table 3.

Table 3 - Per capita IWI across all RC5 regions in 2010 and projected to 2030 and 2050.

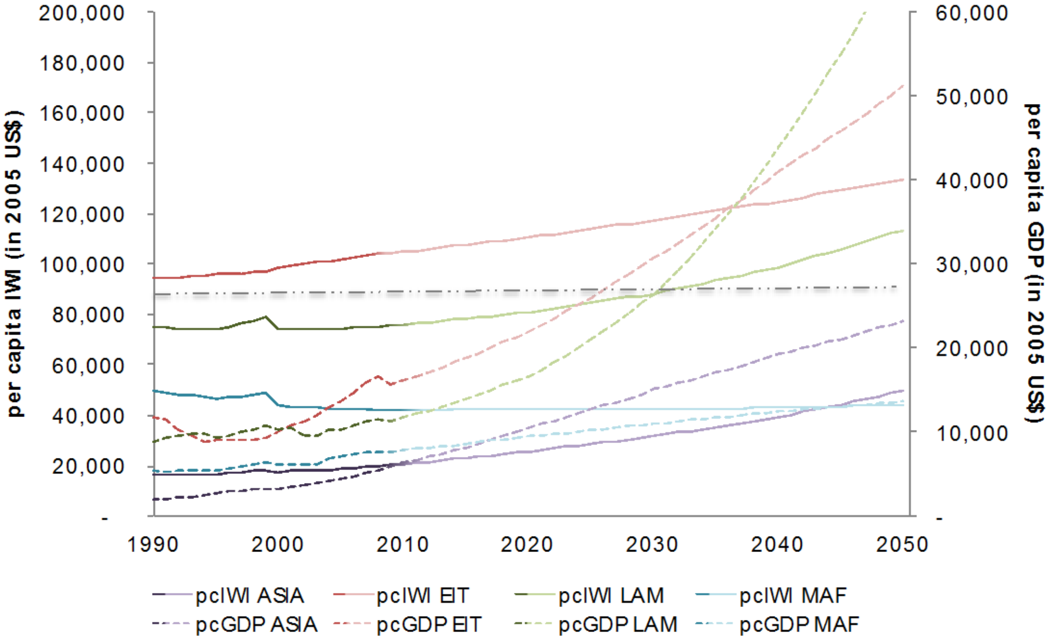
pcIWI **(in 2005 US$)**	**ALL REGIONS**	**ASIA**	**EIT**	**LAM**	**MAF**	**OECD-90**
pop weighted ave. in 2010	92,602	20,779	104,831	75,944	41,956	405,396
median	72,736	17,749	95,038	69,748	31,930	433,946
min	4,627	5,596	4,627	5,627	5,721	75,600
max	758,631	269,065	247,078	139,499	533,044	758,631
pop weighted ave in 2030		31,820	117,308	88,282	42,705	
change 2010-2030		53%	12%	16%	2%	
pop weighted ave in 2050		49,861	133,316	113,558	44,406	
change 2010-2050		140%	27%	50%	6%	

Note: IPCC's RC5 regions: Asia (ASIA) - most Asian countries with the exception of the Middle East, Japan and Former Soviet Union states, Economies in Transition (EIT) – countries from the Reforming Economies of Eastern Europe and the Former Soviet Union, Latin America (LAM) - countries of Latin America and the Caribbean, Middle East and Africa (MAF) - countries of the Middle East and Africa, and OECD 90 countries (OECD90) - countries that were members of the Organization for Economic Co-operation and Development **(**OECD) in 1990. See Appendix D for list of countries.

ASIA and MAF represent the regions with the greatest need for improvement in collective wellbeing, based on their per capita IWI (*pcIWI*) levels. However, our projections indicate that, of the two, only ASIA is on track to achieve significantly higher levels of collective wellbeing by mid-century. This is primarily explained by the fact that, assuming a continuation of the past trend observed, produced capital gains would not only offset all natural capital losses in this region but also allow for a substantial increase in IWI. Meanwhile, MAF would continue to see much shallower growth rates in produced capital and continued losses in natural capital, leading to small improvements in overall wellbeing in this region.

Conversely, LAM and EIT enjoy much higher average per capita IWI (*pcIWI*) levels. However, there are countries in these regions that still bear levels equivalent to the overall minimum, indicating that there is room for relevant improvement in their levels of wellbeing. By contrast, with very high per capita IWI levels and a minimum per capita IWI exceeding the median for all the selected countries in 2010, the OECD90 is not perceived as an area where relevant improvements in wellbeing are needed, and therefore it is not included in the analysis.

Historical and projected per capita IWI and GDP data are plotted alongside to illustrate how wellbeing measured in terms of per capita IWI compares to economic growth in each region (Figure 14). Notably, per capita IWI has grown at much lower rates than per capita GDP in all four regions. This is expected given the changes in the three capital components of IWI, namely natural, human, and produced capital (see section 3.4.2). There was an overall 30 percent decline in natural capital between 1992 and 2010, compared to 56 percent and 8 percent increase in produced and human capital, respectively (UNU-IHDP and UNEP, 2014; p.27).



Note: Observed trends (darker lines) based on historical data from 1990 to 2010 from UNU-IHDP and UNEP (2014) for IWI and from WORLD BANK (2016) for population and GDP. Per capita IWI projections from 2011 onwards (faded lines) are based on extrapolation of IWI growth in the period 1990-2010 in each region and projected population growth from the no-policy baseline scenario of the IAM MESSAGE. Per capita GDP projections (faded lines) are based on estimated growth rates of GDP (PPP) and population from the IAM MESSAGE v.4. Horizontal dashed line refers to the 2010 overall population weighted average *pcIWI* for all one hundred and eighteen countries covered. OECD-1990 countries had over $400,000 *pcIWI* in 2010 (not shown on graph due to scale).

Figure 14 - Observed trends and projections (faded lines) of human wellbeing measured in per capita IWI (*pcIWI*) contrasted with observed trends and projections (faded lines) of per capita GDP (*pcGDP*).

In MAF alone, natural capital reduced over 40 percent compared to growth rates around 10 percent in produced capital and human capital during the same period. By contrast, loss in natural capital (30 percent) was more than offset by increases in produced capital and human capital in ASIA (about 120 and close to 20 percent, respectively). It should be noted, however, that because the IWI framework is based on a production perspective (production-based accounting of natural resource depletion), a region’s IWI could be understating or overstating the value of resources required domestically based on resources flow in international trade interactions.[90]

4.4. Correlating human wellbeing and energy consumption

In order to estimate the additional energy consumption levels associated with the projected levels of wellbeing, we examine how the latter has responded to changes in the former during the observed time period. As such, the relationship between human wellbeing and energy consumption is examined.

Unlike previous studies discussed in section 2.4.2 above, where HDI (or components of it) is used as an indicator of wellbeing and analyzed against energy consumption (or emissions) data, no saturation effect is observed between the two variables. As shown in Figure 15, the relationship between human wellbeing in terms of per capita IWI (*pcIWI*) appears to scale continuously with energy consumption measured in per capita primary energy consumption (*pcEC*) derived from population-weighted energy use data from the World Development Indicators.[91] [92]

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[90] The proponents of the IWI have provided a valuation analysis of natural assets in international trade that provide relevant insights into identifying the drivers of natural capital change and where there could be over- or understatements of the value of resources actually needed by domestic (open) economies for which the IWI was calculated. While resources tend to flow from poor to rich countries, there is no steadfast rule regarding the relationship between income and production or consumption driven depletions (UNU-IHDP AND UNEP, 2012). As such, even though, in general, production entails greater resource depletion than consumption in lower-income, resource-rich economies, it is not exclusively the case (e.g. India, Nicaragua, and Eastern Europe) (UNU-IHDP AND UNEP, 2012).

[91] Energy use refers to use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport (WORLD BANK, 2016). As such, EC refers to primary energy throughout the paper. By using primary energy consumption it will be possible to measure the emission intensities associated with the overall energy supply from primary sources, as opposed to that from final consumers only, whereby energy industries (e.g. the power sector) and non-energy uses are excluded. Moreover, this will allow projected energy consumption rates to be tracked and compared with those associated with minimum quality of life referred to in the literature, in particular SPRENG (2005) and SMIL (2010).

[92] EC = EU converted from koe into GJ: 1 GJ = 1 koe / 1000 x 41.868

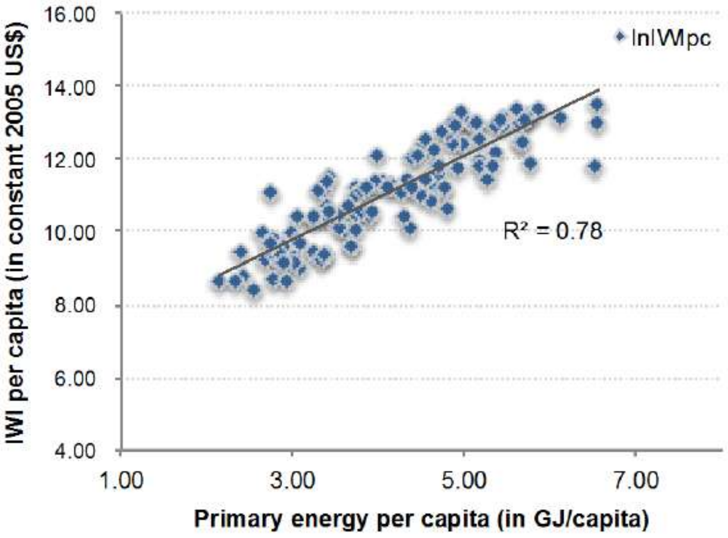

Figure 15 - Correlation between human wellbeing measured in per capita IWI and energy consumption measured in per capita primary energy over the one hundred and eighteen countries covered here for the year 2000 (shown in log-log space).

Source: Prepared by the author using data from UNU-IHDP and UNEP (2014) and WORLD BANK (2016).

As such, a similar approach to that of LAMB AND RAO (2015) is used to mathematically describe the relationship between these two variables.[93] After testing a few different models for goodness of fit, the linear model in log-log form proves to be the best model to describe this relationship and is applied to each of the one hundred and eighteen countries, *i*, as follows:

$$pcIWI_i = \exp(a_i) \times (pcEC_i)^{b_i} \Leftrightarrow \log(pcIWI_i) = a_i + b_i \times \log(pcEC_i) \qquad \textbf{Equation [1]}$$

The log transformation generates the desired linearity in parameters. After estimating the log-log model, the coefficient *b* yields the elasticity of the dependent variable *pcIWI* with respect to the independent variable *pcEC*. In other words, it

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[93] The approach used in this study differs from that in LAMB AND RAO (2015) in that it uses a single indicator of human wellbeing that comprises all three dimensions of sustainable development, instead of three different ones that reflect two dimensions of sustainable development (the environment is not taken into account). Also, the energy consumption data used in this study refer to primary energy, as opposed to final energy, which was used in LAMB AND RAO (2015). Another distinction refers to the regional aggregation used. LAMB AND RAO (2015) applied the data to only three specific sub-regions - Centrally Planned Asia, South Asia, and Africa -, while this study encompassed four broader regions where improvements in wellbeing are still needed.

measures the estimated *percent change* in the dependent variable for a *percent change* in the independent variable. The coefficients obtained for the years 1990, 1995, 2000, 2005, and 2010 are shown in Table 4. They reveal an increase in the elasticity of human wellbeing over time, suggesting an overall decoupling trend for the overall sample of countries. In other words, achieving human wellbeing is becoming steadily more efficient, in line with the findings in STEINBERGER AND ROBERTS (2010).

Table 4 - Regression results from Equation [1].

	R-square	**n**	**% world pop**	**a**	**b**	**p-value of b**
1990	0.64	118	93	7.19	0.98	0.000
1995	0.77	118	93	6.73	1.09	0.000
2000	0.79	118	93	6.56	1.13	0.000
2005	0.78	118	93	6.46	1.13	0.000
2010	0.78	118	93	6.34	1.15	0.000

Note: n = number of countries. Data for the following countries are available from 1991, thus all data refer to 1991 instead of 1990: Croatia, Kazakhstan, Kyrgyzstan, Lithuania, Russian, Federation, Slovenia, Tajikistan, and Ukraine. Data for the following countries are available from 1992, thus all data refer to 1992 instead of 1990: Czech Republic, Slovakia.

For IWI, this decoupling means that the positive impacts of increased energy consumption on the different capitals that comprise the indicator have increasingly outweighed the negative impacts on them between 1990 and 2010. Energy consumption can lead to, or be associated with, increases in produced capital (e.g. investments in infrastructure) (UNU-IHDP and UNEP, 2014). Several studies on the relationship between energy consumption and GDP have found causality running from energy consumption to GDP in several countries (CHEN *et al.*, 2012; OZTURK, 2010), described as the growth hypothesis discussed in section 2.4.1. Increased energy consumption can also promote higher educational levels, as a result of greater access to electricity (e.g. increased hours and flexibility for studying, greater numbers of schools), and thereby increases in human capital (UNU-IHDP and UNEP, 2014).[94]

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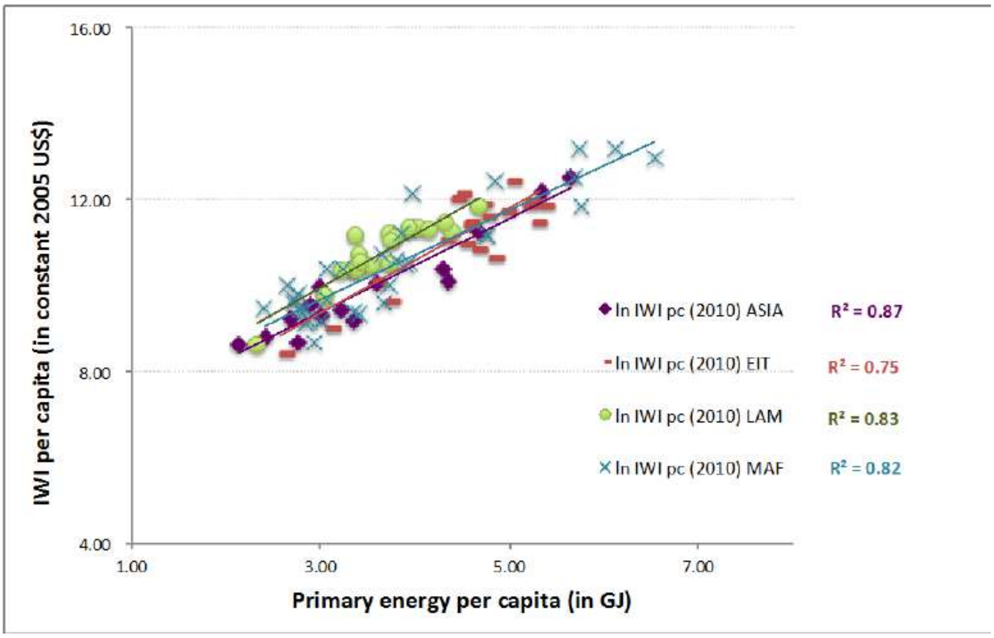
[94] Based on preliminary analyses, the IWR 2014 report (UNU-IHDP and UNEP, 2014) indicates that an increase of 1 percent in energy consumption is associated with a positive variation of 0.64 percent in produced capital and 0.4 percent in human capital.

Conversely, because energy needs have been primarily met through depletion of fossil-fuel deposits,[95] energy consumption has a direct negative impact on IWI's natural capital component. However, these negative impacts have subsided gradually as economies have been transitioning to more efficient and cleaner energy matrices, and thereby reducing their reliance on fossil fuels, albeit at different paces.[96]

We then examine the same relationship in each RC5 region, except in OECD90. As noted in section 4.3, the latter is not perceived as a region where relevant improvements in wellbeing are needed. Notably, the linear model in log-log form continues to fit well in the four regions where improvements in collective wellbeing are still needed, as depicted in Figure 16.



Note: A total of eighty-eight countries were assessed (sixteen in ASIA, twenty-one in EIT, nineteen in LAM, and thirty-two in MAF) after six outliers were removed, as follows: one from EIT, three from LAM, and two from MAF.

Figure 16 - Correlations of human wellbeing measured in per capita IWI (*pcIWI*) and energy consumption measured in per capita energy consumption (*pcEC*) in log-log form across four of the RC5 regions in the year 2010.

Source: Prepared by the author based on data from UNU-IHDP and UNEP (2014) and WORLD BANK (2016).

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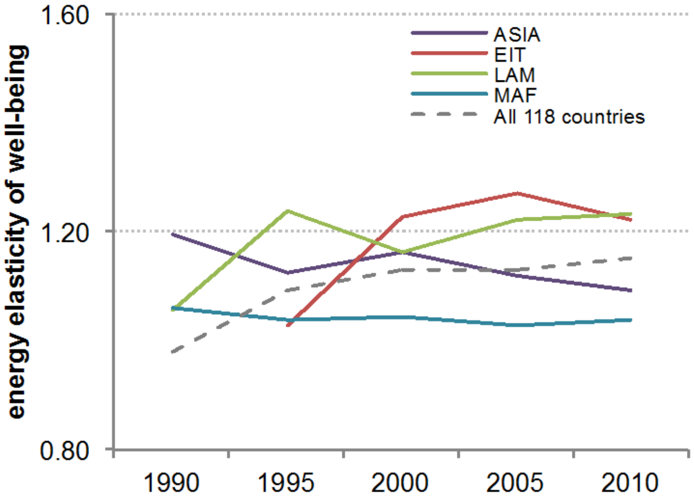
[95] Fossil fuels (oil, coal, and gas) account for 85 percent of total primary energy supplies (BP, 2016).

[96] The contribution of renewable energy sources to the global energy mix has been growing over the last two decades, particularly in the electricity sector (IRENA, 2016).

On the other hand, the decoupling trend does not prove consistent in all regions. ASIA has mostly seen decreasing elasticities overtime and MAF has not seen much variation, as depicted in Figure 17. This suggests that the negative impacts of increased energy consumption on IWI's natural capital have increasingly outweighed and offset its positive impacts on IWI's produced and human capitals in ASIA and MAF, respectively. This is in part a result of large deployment of fossil fuels, which have prevailed in particular in ASIA's energy mix (BP, 2016).[97] Meanwhile for MAF, the negative impacts on IWI's natural capital seem to have been mostly compensated by the positive ones on the other two capitals, on a per capita basis. This is likely due to continued high share of fossil fuels in the energy mix of the region (WORLD BANK, 2017), as well as, a result of the higher than average population growth rate seen in this region during this period (UNU-IHDP and UNEP, 2014).



Note: Sixteen countries were assessed in ASIA, twenty-one in EIT, nineteen in LAM, and thirty-two in MAF, after six outliers were removed, as follows: one from EIT, three from LAM, and two from MAF. The dashed line refers to the elasticities obtained in the assessment of all one hundred and eighteen countries (see Table 4). Key: An elasticity of 1.20 means that for each 1 percent change in energy consumption (*pcEC*), there was a 1.20 percent change in wellbeing (*pcIWI*).

Figure 17 - Change in elasticity *(b* values) over time.

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[97] Exceptionally between 1995 and 2000, the energy elasticity of well-being increased in Asia, as depicted in Figure 17. This can be explained by the temporary decline in coal consumption seen in this period, believed to have been caused by a combination of the following factors: a general economic slowdown that resulted from the Asian crisis, higher coal quality, systematic closures of inefficient state-owned facilities, a general increase in end-use efficiency, as well as some substitution of coal for gas (SINTON AND FRIDLEY, 2000).

4.5. Estimating the additional energy needed and associated carbon emissions

The fit parameters obtained through the regression runs obtained in Section 4.4 could be linearly projected to generate future elasticities, which could in turn be used to estimate the additional energy consumption associated with future improvements in human wellbeing in each of the selected four regions. By doing so, specific aspects affecting the relationship between energy consumption and IWI in each region would be taken into consideration. For instance, natural capital is directly impacted by energy consumption, however its share in the IWI composition varied from 8 to 40 percent in average in the period from 1990 to 2010 depending on the region.[98]

However, by doing so, the analysis could be distorted by unique systemic events that are unlikely to repeat in the future and would not take into consideration different possibilities throughout the forecast period. Therefore, a sensitivity range is devised for each region instead, using the highest observed decrease rate in elasticity (coefficient *b*) to progressively decrease elasticities from 2011 to 2020 and maintaining it constant thereafter as the upper bound, and the highest observed increase rate in elasticity to progressively increase elasticities from 2011 to 2020 and maintaining it constant thereafter as the lower bound (see Table 5). Thereby, regional differences are still taken into consideration while allowing for annual fluctuations in future elasticities.

Table 5 - Compound annual rates of change (%) in elasticity.

	ASIA	EIT	LAM	MAF
1990-1995	-1.266		3.193	-0.455
1995-2000	0.713	3.646	-1.257	0.181
2000-2005	-0.798	0.675	1.079	-0.343
2005-2010	-0.499	-0.781	0.150	0.184
Upper bound				
2011-2020	-0.635	-0.391	-0.631	-0.228
Lower bound				
2011-2020	0.356	0.337	0.538	0.092

Notes: No elasticity change calculated for 1990-1995 in EIT since the

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[98] Calculated based on natural capital data from UNU-IHDP and UNEP (2014).

linear model did not fit well for the 1990 data. Positive change denotes decoupling trend between energy consumption (*pcEC*) and wellbeing (*pcIWI*). Upper bound rates calculated based on prorated highest decrease rates observed, applied in the 10-year period 2011-2020. Lower bound rates calculated based on prorated highest increase rates observed, applied in the 10-year period 2011-2020. Second highest rates used to avoid distortions from peaks in EIT and LAM.

By applying equation 1 and the two levels of change in elasticity (lower and upper bounds in Table 5) to annually *projected pcIWI* (in 2005US$) for each region, *j* (see section 4.3), the estimated lower and upper bounds of the range of projected per capita primary energy consumption (*projected pcEC*) are obtained for each year after 2010, as follows:

$$projectedpcEC_j = \exp\left(\frac{\left(\log\left(projectedpcIWI_j\right) - a\right)}{b}\right) \qquad \textbf{Equation [2]}$$

The *projected pcEC* for each region, *j*, for the years 2011 through 2050 are then calibrated to the historical primary energy consumption data by applying their growth rates starting with the last observed value of *pcEC*, i.e. in 2010, which was obtained from a population-weighted energy use data from the World Development Indicators (WORLD BANK, 2016). By doing this, we adjust the projections to likely differences in data sources, regional boundaries and other assumptions used in the IAM MESSAGE v.4 projections, following the same approach taken by LAMB AND RAO (2015).

The normalized values of the *projected pcEC* (*Nprojected pcEC*) are then scaled by population to derive overall annual primary energy consumption levels (*projected EC*) for each region, *j*, using normalized population projections from the IAM MESSAGE (*NprojectedPOP*),[99] as follows:

$$projectedEC_j = NprojectedpcEC_j \times NprojectedPOP_j \qquad \textbf{Equation [3]}$$

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[99] As noted in section 4, all IAM MESSAGE data were obtained from the LIMITS Scenario Database (LIMITS Database, 2016) and confirmed in IPCC’s AR5 Scenario Database (IAMC AR5 Scenario Database, 2014).

Subsequently, the associated carbon emissions (*projected CO_2 emissions*) are estimated for each region, *j*, by applying normalized CO_2 emission intensities projections from the same no-policy baseline scenario of the IAM MESSAGE (IAMC AR5 Scenario Database, 2014; LIMITS Database, 2016) to the *projected EC*, as follows:

$$projectedCO_2emissions_j = projectedEC_j \times NprojectedCO_2emission\ intensities_j$$

Equation [4]

The normalized projected CO_2 emission intensities (*Nprojected CO_2 emission intensities*) are calculated based on projected CO_2 emissions from fossil fuel combustion and industrial processes and primary energy data from the no-policy baseline scenario of the IAM MESSAGE v.4 (IAMC AR5 Scenario Database, 2014; LIMITS Database, 2016),[100] normalized to that of 2010 based on four sets of growth rates for each region, as shown in Table 6.

Table 6 - Compound annual rates of change (%) in CO_2 emission intensity.

	ASIA	EIT	LAM	MAF
2011-2020	0.31	-0.04	0.61	0.18
2021-2030	0.19	0.15	0.03	-0.13
2031-2040	0.14	0.07	0.51	-0.07
2041-2050	0.00	0.04	-0.41	0.05

Source: own calculations based on projected CO_2 emissions from fossil fuel combustion and industrial processes and primary energy consumption data from LIMITS Database (2016) and IAMC AR5 Scenario Database (2014).

Following the calculations above, the lower and upper bounds of *projected CO_2 emissions* for each of the four regions are obtained for each year of the projection period, i.e. from 2011 to 2050.

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[100] The Scenario Base (or no-policy baseline) in the LIMITS project refers to the standard no climate policy baseline run, which reflects development and emissions pathways unconstrained by mitigation actions (KRIEGER *et al*., 2013, TAVONI *et al*., 2014).

5. Results

Results of the quantitative assessment described above are presented in this chapter. The estimated CO_2 emissions required for higher levels of collective wellbeing are then compared with regional emissions pathways based on two stabilization scenarios from the same integrated assessment model used in the quantitative assessment (the IAM MESSAGE used in the LIMITS project) (section 5.2).

These two stabilization scenarios provide the two carbon budgets, against which estimated additional carbon emissions (*projected CO_2 emissions*) associated with future improvements in human wellbeing assuming different climate policy scenarios are compared to (section 5.3).

5.1. Additional energy needed and associated emissions

Table 7 presents the estimated additional primary energy consumption (*projected EC*) and the associated carbon emissions (*projected CO_2* emissions) resulting from the projected future improvements in human wellbeing in each of the four selected regions by 2030 and 2050.

Table 7 - Annual results from Equations [3] and [4].

	n	**% world pop**	***Projected EC* (EJ/year)**				***Projected CO_2 emissions* ($GtCO_2$/year)**			
			By 2030		**By 2050**		**By 2030**		**By 2050**	
			lower	*upper*	*lower*	*upper*	*lower*	*upper*	*lower*	*upper*
ASIA	16	52	265	393	418	645	19.5	28.9	31.3	48.2
MAF	32	13	71	80	95	108	4.0	4.6	5.4	6.1
LAM	19	8	35	57	45	75	1.9	3.1	2.5	4.1
EIT	21	5	46	66	48	69	2.8	4.0	3.0	4.3
Total	88	78	417	596	606	897	28.3	40.7	42.1	62.8

Notes: n = number of countries (6 outliers removed: 2 from MAF, 3 from LAM, 1 from EIT). Projected EC = estimated additional primary energy consumption in Exajoule (EJ).

Overall, the four regions combined would require between 417 and 596 EJ in primary annual energy consumption and between 28.3 and 40.7 $GtCO_2$ in annual carbon emissions by 2030 to increase current levels of wellbeing and between 606 and 897 EJ and between 42.1 and 62.8 $GtCO_2$ by 2050 to improve it even further. Their cumulative values are presented in table 8.

Table 8 - Cumulative results from Equations [3] and [4].

	n	**% world pop**	***Projected EC* (EJ)**				***Projected CO_2 emissions* ($GtCO_2$)**			
			2011-2030		**2011-2050**		**2011-2030**		**2011-2050**	
			lower	*upper*	*lower*	*upper*	*lower*	*upper*	*lower*	*upper*
ASIA	16	52	4,293	5,859	11,088	16,154	285	424	817	1,192
MAF	32	13	1,200	1,3289	2,859	3,214	63	76	162	183
LAM	19	8	644	942	1,444	2,267	31	51	80	125
EIT	21	5	933	1,225	1,874	2,581	51	75	115	158
Total	88	78	7,070	9,366	17,264	24,216	430	626	1,174	1,658

Notes: n = number of countries (6 outliers removed: 2 from MAF, 3 from LAM, 1 from EIT). Projected EC = estimated additional primary energy consumption in Exajoule (EJ).

In terms of cumulative values the four regions combined would require between 7,070 and 9,366 EJ in overall primary energy consumption and between 430 and 626 $GtCO_2$ in overall carbon emissions from 2011 to 2030 and between 17,263 and 23,871 EJ and between 1,174 and 1,658 $GtCO_2$ from 2011 to 2050 to achieve higher collective wellbeing. Ultimately, cumulative emissions are what matters most in terms of meeting the climate stabilization targets (MEINSHAUSEN *et al.*, 2009; KRIEGLER *et al.*, 2013; KNUTTI AND ROGELJ, 2015; ROGELJ *et al.*, 2016b).

A comparison with previous quantification efforts in the literature that used HDI or components of it as proxy for human wellbeing is provided in Appendix E. The energy levels estimated in the present study are at least 23 percent higher than previous quantifications found in the literature (PASTERNAK, 2000; UGURSAL, 2014) and the CO_2 emissions estimates are at least 38 percent higher than previous quantifications (COSTA *et al.*, 2011; LAMB AND RAO, 2015).

5.1.1. In ASIA

Representing by far the largest region in terms of population, ASIA alone would account for approximately 61 to 67 percent of the estimated additional primary energy consumption needed and 66 to 72 percent of the associated carbon emissions.

According to the results obtained, achieving increased levels of human wellbeing in ASIA would entail between 265 and 393 EJ (63-94 GJ/capita) in primary annual energy consumption and between 19.5 and 28.9 $GtCO_2$ in annual carbon emissions by 2030, and 418-645 EJ (94-146 GJ/capita) and between 31.3 and 48.2 $GtCO_2$ by 2050. In terms of cumulative energy consumption and carbon emissions, the projected pathways for this region indicate a total of at least 4,293 EJ and 285 $GtCO_2$ in the 2011-2030 period, and 11,088 EJ and 817 $GtCO_2$ in 2011-2050. These levels are associated with an increase of 53 percent in wellbeing in per capita IWI (*pcIWI*) between 2010 and 2030 and 140 percent between 2010 and 2050 (see Table 4 in section 4.3).

Even though the absolute values of *pcIWI* cannot provide a direct indication of whether ASIA would achieve a sufficiently high level of wellbeing, the scale of its relative change (53 percent) and the average primary energy consumption rate reached already in 2030 point to a significant achievement. According to the projections obtained in this analysis, the primary energy consumption rate in ASIA is expected to increase from 49 to at least 63 and up to 94 GJ/capita between 2010 and 2030, thus likely moving out of the energy poverty levels discussed in section 2.2 before mid-century.

5.1.2. In the Middle East and Africa (MAF)

The second largest region, MAF, representing 13 percent of the world population, would require between 71 and 80 EJ (53-61 GJ/capita) in primary annual energy consumption and between 4.0 and 4.6 $GtCO_2$ in annual carbon emissions by 2030 to practically sustain current levels of wellbeing in *pcIWI.* It would then require between 95 and 108 EJ (55-63 GJ/capita) and between 5.4 and 6.1 $GtCO_2$ by 2050 to improve wellbeing by 6 percent (see Table 4 in section 4.3). In terms of cumulative energy consumption and carbon emissions, the projected pathways for MAF indicate a total of at least 1,200 EJ and 63 $GtCO_2$ in the 2011-2030 period, and 2,859 EJ and 162 $GtCO_2$ in 2011-2050.

Unlike ASIA, MAF is unlikely to move out of the energy poverty levels discussed in section 2.2 between 2010 and 2030 since its average primary energy consumption rate would increase from 54 to up to 61 GJ/capita in the same period according to the projections obtained in this analysis. In fact, not even the projections into 2050 indicate any likelihood of the region moving much further out of the energy poverty levels. Its primary energy consumption rate would increase to up to 63 GJ/capita by 2050.

5.1.3. In Latin America (LAM)

LAM follows next in population size, accounting for 8 percent of the world population. Achieving a 16 percent increase in wellbeing by 2030 in this region would entail between 35 and 57 EJ (51-83 GJ/capita) in average primary annual energy consumption and between 2.4 and 3.1 $GtCO_2$ in annual carbon emissions by the same year. Similarly, achieving a 50 percent increase by mid-century would entail between 45 and 75 EJ (61-103 GJ/capita) in average primary annual energy consumption and between 2.5 and 4.1 $GtCO_2$ by then. In terms of cumulative energy consumption and carbon emissions, the projected pathways for this region indicate a total of at least 644 EJ and 31 $GtCO_2$ in the 2011-2030 period, and 1,444 EJ and 80 $GtCO_2$ in 2011-2050.

According to the projections obtained in this analysis, the expected range of increase from 56 to up to 83 GJ/capita between 2010 and 2030 indicates that, similar to ASIA, LAM is also likely to move out of the energy poverty levels discussed in section 2.2 before mid-century.

5.1.4. In Economies in Transition (EIT)

The fourth and last region assessed, representing only 5 percent of the world population, EIT would require between 46 and 66 EJ (139-199 GJ/capita) in average primary annual energy consumption and imply in annual carbon emissions between 2.8 and 4.0 $GtCO_2$ by 2030 to increase current levels of wellbeing by 12 percent, and between 48 and 69 EJ (154-222 GJ/capita) and 3.0 and 4.3 $GtCO_2$ by 2050 to improve it by 27 percent. In terms of cumulative energy consumption and carbon emissions, the projected pathways for EIT indicate a total of at least 933 EJ and 51 $GtCO_2$ in the 2011-2030 period, and 1,874 EJ and 115 $GtCO_2$ in 2011-2050, as shown in Figure 18b.

Clearly, this region not only already enjoys the highest levels of wellbeing among the four regions under analysis in both absolute per capita IWI terms, as well as, in terms of energy consumption rates, but is also set to improve them even further.

5.2. Wellbeing versus climate stabilization: comparing emissions pathways

The calculations used to estimate the CO_2 emissions associated with bridging the energy divide and achieving higher collective wellbeing assumed CO_2 emission intensities based on data from the no-policy baseline scenario of the IAM MESSAGE v.4. This scenario refers to the standard no climate policy and target baseline run of the model. It reflects no new climate policy or mitigation action beyond what has already been put in place (as of 2010). As such, the results of equation 4 (*projected* CO_2 *emissions*) provided in sections 5.1 and 5.2 refers to a No-action scenario, and thus reflect prevailing technologies and decarbonisation rates.

5.2.1. Associated emissions under no-action scenario

In order to determine whether the estimated carbon emissions needed to achieve higher levels of collective wellbeing would affect existing carbon budgets, their emission pathways were compared with regional emissions pathways associated with the 2 °C climate stabilization target. Notably, over one hundred climate policy scenarios have been produced in the literature based on different probabilities of reaching this target (CLARKE *et al.*, 2014, Kriegler *et al.*, 2014b), as discussed in section 2.3.2. In fact, there are many different emissions pathways and timings associated with meeting different intended climate stabilization targets (ROGELJ *et al.*, 2011, 2015 and 2016b; CLARKE *et al.*, 2014; DESSENS *et al.*, 2014; UNEP, 2015).[101]

For this assessment, two stabilization scenarios from the same IAM used in the

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[101] Emissions profiles in the existing modeling literature are determined by three interrelated factors: (1) the degree of overshoot, (2) technology options and associated deployment decisions, and (3) policy assumptions (CLARKE *et al.*, 2014).

quantitative analysis above (the IAM MESSAGE used in the LIMITS project) were used (IAMC AR5 Scenario Database, 2014; LIMITS Database, 2016), namely: Scenario 450 and Scenario 500, which are associated with reasonably high and even chances of meeting the 2 ^{o}C climate stabilization target, respectively (TAVONI *et al*., 2014). These two stabilization scenarios are hereinafter referred to as Immediate action-450 and Immediate action-500, respectively.

These two stabilization scenarios provide the two carbon budgets used in this assessment, i.e. the 450-ppm and 500-ppm budgets. In both scenarios, even though energy consumption is set to increase, CO_2 emissions would fall below the levels that our assessment indicated would be required to achieve and sustain higher collective wellbeing in all four regions by mid-century (Figure 18). This is most noticeable in ASIA, where the estimated gap could range from 23 to 43 $GtCO_2$ by mid-century and is much higher than the range of 7 to 12 $GtCO_2$ estimated for the other three regions combined.

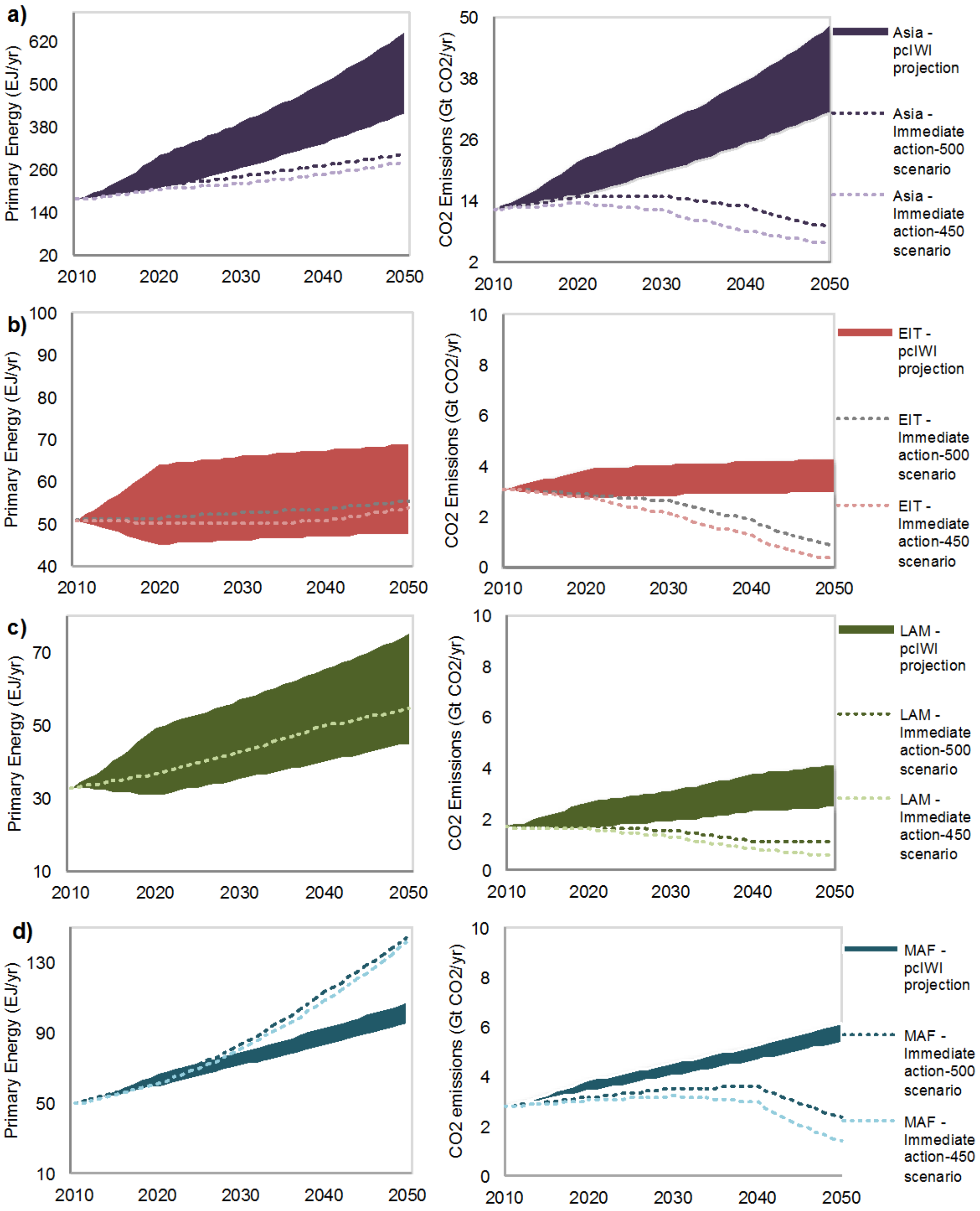
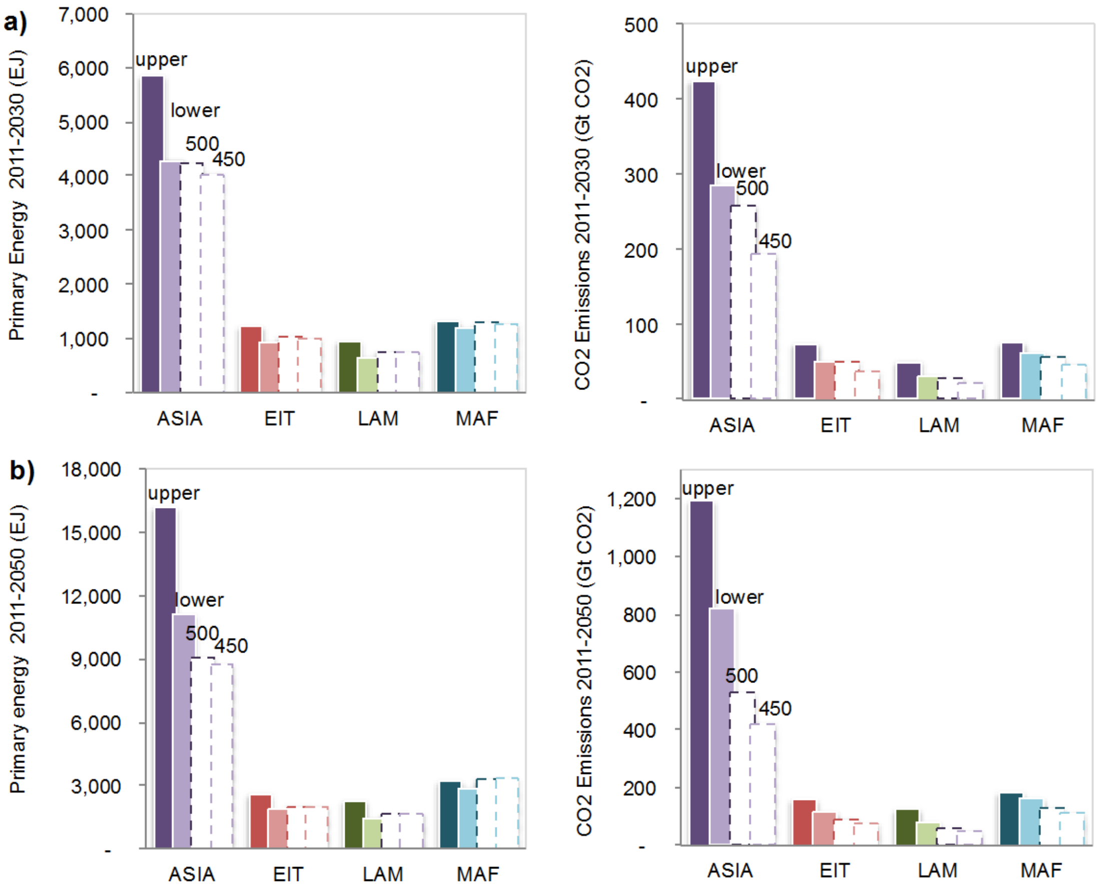


Figure 18 - Estimated annual primary energy and CO₂ emissions pathways for achieving higher levels of human wellbeing in ASIA, EIT, LAM, and MAF, compared to two stabilization scenarios from the IAM MESSAGE (Immediate action-450 and Immediate action-500), which would yield reasonably high and even chances of achieving 2ºC, respectively.

Sources: own calculations following the quantitative assessment presented in section 4.5 and IAMC AR5 Scenario Database (2014) and LIMITS Database (2016) for policy scenarios.

In both climate policy scenarios, cumulative emissions fall short of the estimated amounts required for achieving higher levels of collective wellbeing, primarily in ASIA, where the gap could be at least 26 $GtCO_2$ and as high as 231 $GtCO_2$ between 2011 and 2030 (Figure 19a) and at least 291 $GtCO_2$ and as high as 771 $GtCO_2$ between 2011 and 2050 (Figure 19b). By contrast, the largest gaps in the other three regions combined would not exceed about 95 $GtCO_2$ in the first period and about 232 $GtCO_2$ in the second one.



Note: The shaded bars refer to the upper (darker tone) and lower (lighter tone) bounds of the sensitivity range of the projection.

Figure 19 - Estimated cumulative primary energy and CO_2 emissions for achieving higher levels of human wellbeing in ASIA, EIT, LAM, and MAF in 2011-2030 and 2011-2050, compared to two standard benchmark policy scenarios from the IAM MESSAGE v.4 (Immediate action-450 and Immediate action-500), which are associated with reasonably high and even chances of meeting the 2 °C target, respectively.

Sources: own calculations following the quantitative assessment presented in section 4.5 and IAMC AR5 Scenario Database (2014) and LIMITS Database (2016) for policy scenarios.

As discussed in section 4.3 above, with population-weighted averages of per capita IWI expected for 2050 still close to half of the overall average from 2010, ASIA and MAF are the regions with the greatest need for improvement in collective wellbeing. However, based on the projections obtained here, of the two, only ASIA would be able to achieve substantial improvements in the period under analysis, primarily due to the fact that, assuming a continuation of the past trend observed, produced capital gains would not only offset all natural capital losses in this region but also allow for a substantial increase in IWI. Hence, the expected 53 percent increase in per capita IWI in the region already by 2030.

Meanwhile, given much shallower growth rates in produced capital and continued losses in natural capital, overall per capita IWI in MAF is only expected to see mere 2 percent and 6 percent increases by 2030 and 2050, respectively. This explains the expected small gap ranges between cumulative emissions in the two policy scenarios and those required to achieve higher levels of collective wellbeing in this region of at least 5 and up to 30 $GtCO_2$ in the first period (2011 to 2030) and at least 35 and up to 71 $GtCO_2$ in the second one (2011 to 2050).

In any case, in spite of MAF's expected inability to achieve a significantly high level of human wellbeing by mid-century, the small improvements projected for this region could exceed the emissions budget for the region by over 60 percent, i.e. 183 $GtCO_2$ in the upper bound projection from this analysis compared to 112 $GtCO_2$ in the most stringent of the two climate policy scenarios (Immediate action-450).

Considering all four regions combined and the emission pathways of the two IAM MESSAGE stabilization scenarios associated with reasonably high and even chances of limiting the temperature increase to below 2 ^{o}C, Immediate action-450 and Immediate action-500, the corresponding overall carbon budgets could be exceeded by as much as two and a half times (1,003 $GtCO_2$) and about two times (856 $GtCO_2$) by mid-century, respectively.

5.2.2. Climate action scenarios

In order to help us determine what can be done to bridge the energy divide and achieve higher levels of wellbeing while staying within the carbon budget, we looked at three alternative scenarios from the IAM MESSAGE v.4, wherein new climate policy and actions are considered to project future CO_2 emissions associated with higher collective wellbeing, namely: Action as of 2020-500 (RefPol-500 in the LIMITS project), Action as of 2020-450 (RefPol-450 in the LIMITS project), and Delayed action-500 (RefPol2030-500 in the LIMITS project). These three climate policy scenarios are discussed in the next sections. All six scenarios used in this analysis are summarized in Table 9.

Table 9 - Emissions scenarios.

Scenario name	Corresponding scenario in LIMITS study	Scenario type	Fragmented action until	Long-term target (2100)
No-action	Base	Baseline	n/a	none
Immediate action-500	500	Stabilization	n/a	500 ppm CO_2eq (3.2 W/m^2)
Immediate action-450	450	Stabilization	n/a	450 ppm CO_2eq (2.8 W/m^2)
Action as of 2020-500	RefPol-500	Climate policy	2020	500 ppm CO_2eq (3.2 W/m^2)
Action as of 2020-450	RefPol-450	Climate Policy	2020	450 ppm CO_2eq (2.8 W/m^2)
Delayed action-500	RefPol-2030-500	Climate policy	2030	500 ppm CO_2eq (3.2 W/m^2)

Source: Adapted from KRIEGLER *et al*., 2013.

5.2.3. Associated emissions under Action as of 2020-500 scenario

The Action as of 2020-500 scenario (RefPol-500 in the LIMITS project) refers to a scenario where regions follow existing domestic policies or mitigation actions until 2020 and adopt new policies and actions associated with even chances of meeting the 2 °C target, i.e. reaching GHG concentrations at roughly 500 ppm CO_2e in 2100, thereafter.

New projected CO_2 emission intensities (*Nprojected CO_2 emission intensities*) are calculated based on projected CO_2 emissions from fossil fuel combustion and industrial processes and primary energy data from the RefPol-500 of the IAM MESSAGE v.4 (IAMC AR5 Scenario Database, 2014; LIMITS Database, 2016), normalized to that of 2010 based on four sets of growth rates for each region, as shown in Table 10.

Table 10 - Compound annual rates of change (%) in CO_2 emission intensity on the Action as of 2020-500.

	ASIA	EIT	LAM	MAF
2011-2020	-0.08	-0.48	-1.48	-0.06
2021-2030	-0.74	-2.06	-1.92	-2.14
2031-2040	-3.05	-3.91	-4.26	-2.85
2041-2050	-5.01	-12.25	-42.52	-6.46

Source: own calculations based on projected CO_2 emissions from fossil fuel combustion and industrial processes and primary energy consumption data from the RefPol-500 scenario of the IAM MESSAGE v.4 (IAMC AR5 Scenario Database, 2014; LIMITS Database, 2016).

Following the calculations in section 4.5 and applying the revised projected CO_2 emission intensities for Action as of 2020-500 scenario as per above to equation 4, the estimated CO_2 emissions pathways for achieving higher levels of human wellbeing are revised, as shown in Figure 20.

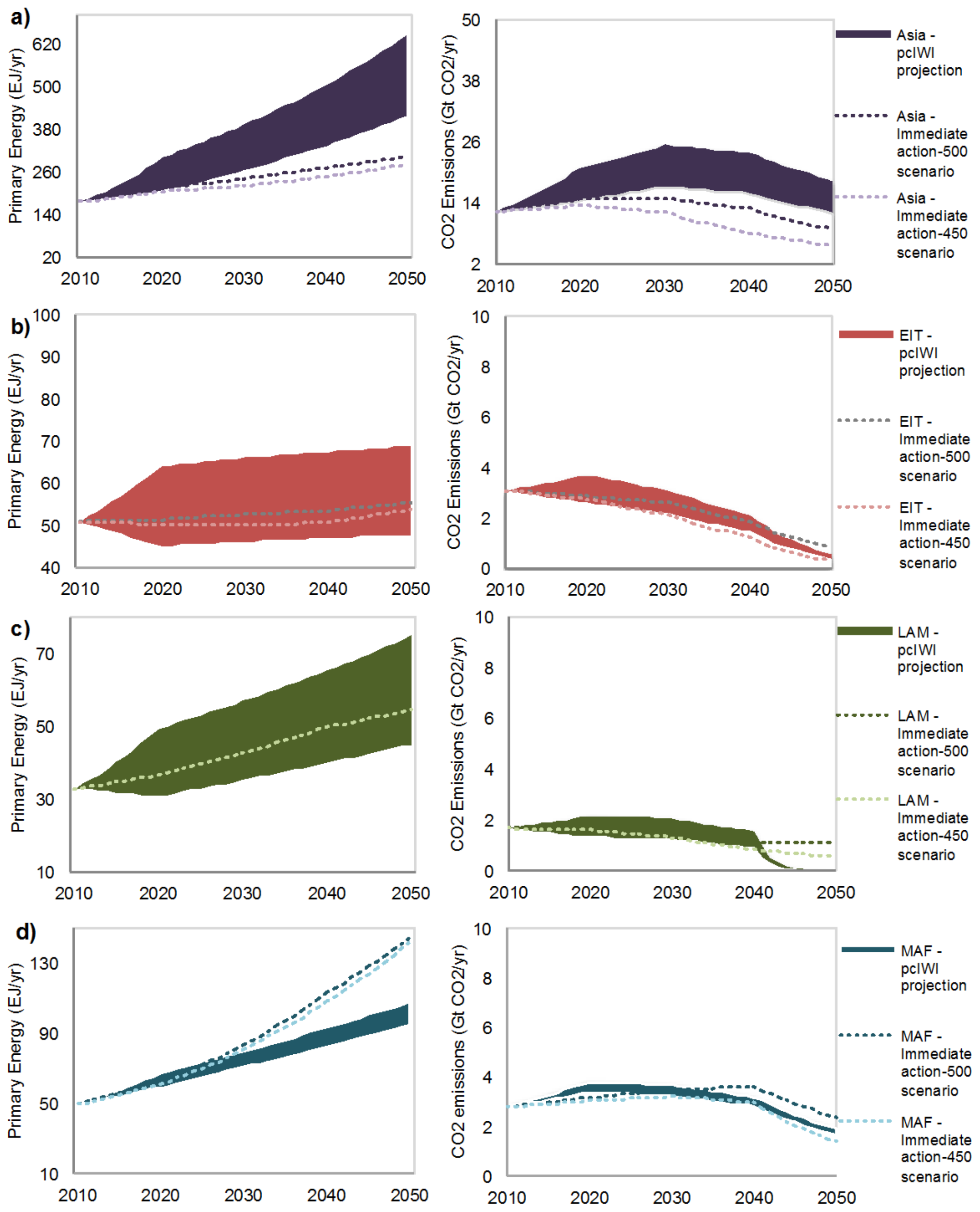


Figure 20 - Estimated annual primary energy and CO$_2$ emissions for achieving higher levels of human wellbeing in ASIA, EIT, LAM, and MAF in the Action as of 2020-500, compared to projections based on two stabilization scenarios from the IAM MESSAGE (Immediate action-450 and Immediate action-500), which would yield reasonably high and even chances of achieving 2ºC, respectively.

Sources: own calculations following the quantitative assessment presented in section 4.5 and revised projected CO$_2$ emission intensities for the Action as of 2020-500 scenario; and IAMC AR5 Scenario Database (2014) and LIMITS Database (2016) for policy scenarios.

5.2.4. Associated emissions under Action as of 2020-450 scenario

The Action as of 2020-450 scenario (RefPol-450 in the LIMITS project) refers to a scenario where regions follow existing domestic policies or mitigation actions until 2020 and adopt new policies and actions associated with reasonably high chances of meeting the 2 °C target, i.e. reaching GHG concentrations at roughly 450 ppm CO2e in 2100, thereafter.

New projected CO_2 emission intensities (*Nprojected CO_2 emission intensities*) are calculated based on projected CO_2 emissions from fossil fuel combustion and industrial processes and primary energy data from the RefPol-450 of the IAM MESSAGE v.4 (IAMC AR5 Scenario Database, 2014; LIMITS Database, 2016), normalized to that of 2010 based on four sets of growth rates for each region, as shown in Table 11.

Table 11 - Compound annual rates of change (%) in CO_2 emission intensity on the Action as of 2020-450.

	ASIA	EIT	LAM	MAF
2011-2020	-0.08	-0.48	-1.48	0.06
2021-2030	-1.75	-3.45	-3.14	-2.88
2031-2040	-5.27	-6.50	-5.88	-4.09
2041-2050	-6.56	-17.46	-40.79	-10.70

Source: own calculations based on projected CO_2 emissions from fossil fuel combustion and industrial processes and primary energy consumption data from the RefPol-450 scenario of the IAM MESSAGE v.4 (IAMC AR5 Scenario Database, 2014; LIMITS Database, 2016).

Following the calculations in section 4.5 and applying the revised projected CO_2 emission intensities as per above to equation 4, the estimated CO_2 emissions pathways for achieving higher levels of human wellbeing are revised, as shown in Figure 21.

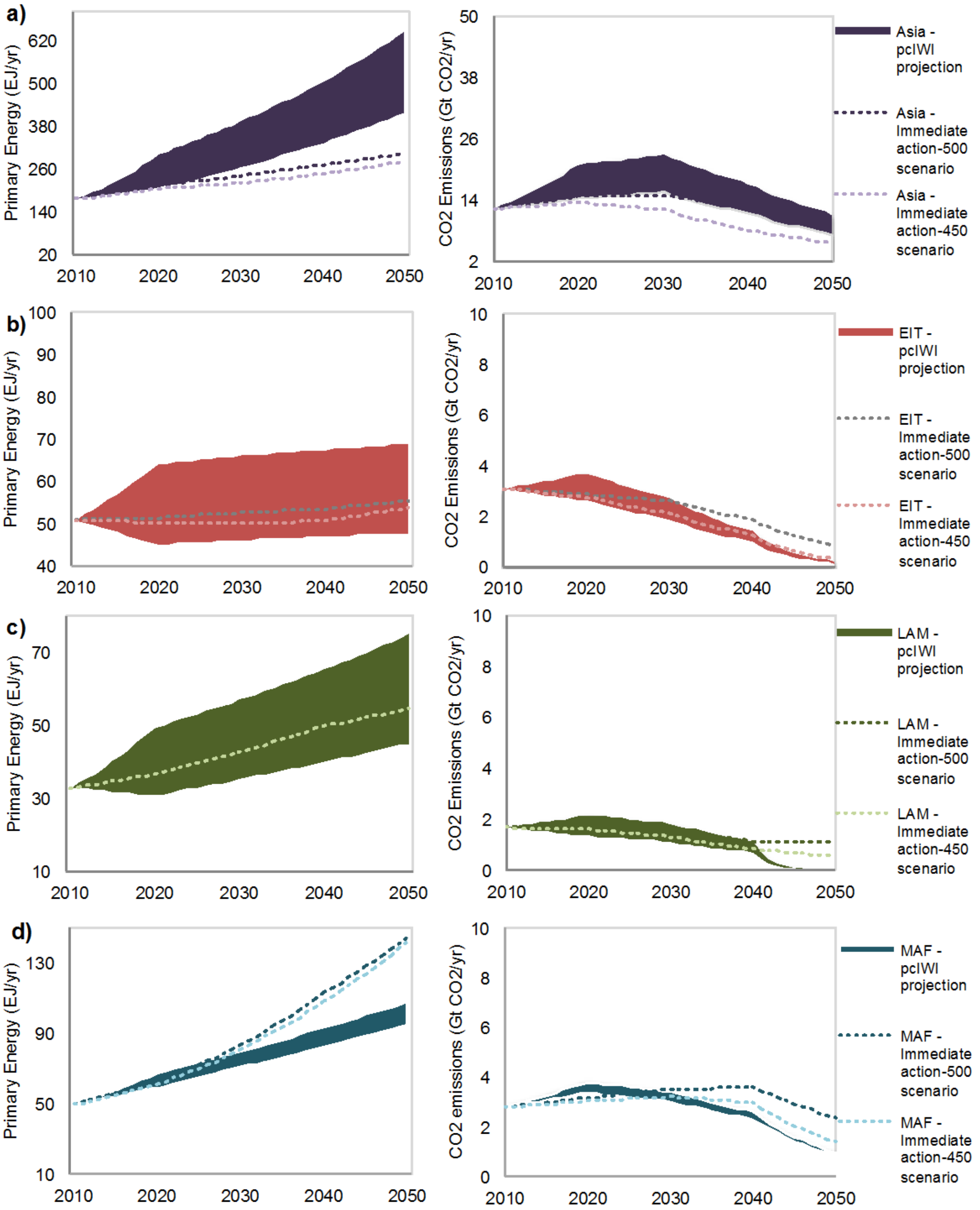


Figure 21 - Estimated annual primary energy and CO_2 emissions for achieving higher levels of human wellbeing in ASIA, EIT, LAM, and MAF in the Action as of 2020-450, compared to projections based on two stabilization scenarios from the IAM MESSAGE (Immediate action-450 and Immediate action-500), which would yield reasonably high and even chances of achieving 2°C, respectively.

Sources: own calculations following the quantitative assessment presented in section 4.5 and revised projected CO_2 emission intensities for Action as of 2020-450 scenario; and LIMITS Database (2016) and IAMC AR5 Scenario Database (2014) for policy scenarios.

5.2.5. Associated emissions under Delayed action-500 scenario

The Delayed action-500 scenario (RefPol2030-500) refers to a scenario where regions follow existing domestic policies or mitigation actions until 2030 and adopt new policies and actions associated with even chances of meeting the 2 ^{o}C target, i.e. reaching GHG concentrations at roughly 500 ppm CO2e in 2100, only thereafter.

New projected CO_2 emission intensities (*Nprojected CO_2 emission intensities*) are calculated based on projected CO_2 emissions from fossil fuel combustion and industrial processes and primary energy data from the RefPol2030-500 scenario of the IAM MESSAGE (IAMC AR5 Scenario Database, 2014; LIMITS Database, 2016), normalized to that of 2010 based on four sets of growth rates for each region, as shown in Table 12.

Table 12 - Compound annual rates of change (%) in CO_2 emission intensity on the Delayed action-500 scenario.

	ASIA	EIT	LAM	MAF
2011-2020	-0.08	-0.48	-1.48	0.06
2021-2030	0.19	-0.02	-0.53	-0.21
2031-2040	-3.19	-4.18	-3.08	-2.57
2041-2050	-4.77	-11.81	-9.75	-4.27

Source: own calculations based on projected CO_2 emissions from fossil fuel combustion and industrial processes and primary energy consumption data from the RefPol2030-500 scenario of the IAM MESSAGE (IAMC AR5 Scenario Database, 2014; LIMITS Database, 2016).

Following the calculations in section 4.5 and applying the revised projected CO_2 emission intensities as per above to equation 4, the estimated CO_2 emissions pathways for achieving higher levels of human wellbeing are revised, as shown in Figure 22.

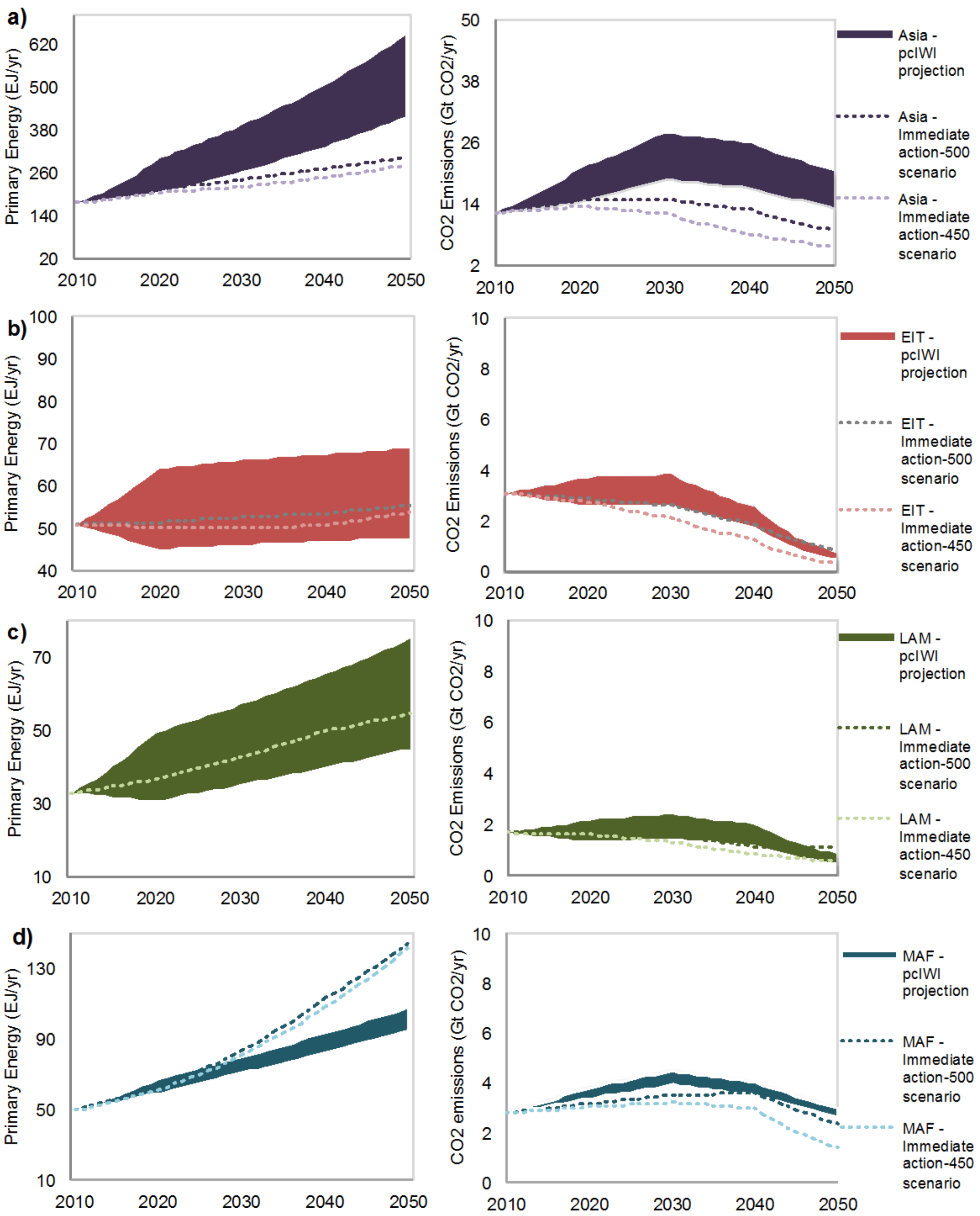


Figure 22 - Estimated annual primary energy and CO$_2$ emissions for achieving higher levels of human wellbeing in ASIA, EIT, LAM, and MAF in the Delayed action-500 scenario, compared to projections based on the stabilization scenarios from the IAM MESSAGE (Immediate action-450 and Immediate action-500), which would yield reasonably high and even chances of achieving 2ºC, respectively.

Sources: own calculations following the quantitative assessment presented in section 4.5 and revised projected CO$_2$ emission intensities for the Delayed action-500 scenario; and LIMITS Database (2016) and IAMC AR5 Scenario Database (2014) for policy scenarios.

5.3. Wellbeing versus climate stabilization: assessing the gaps

As noted in section 5.2.1, the two climate stabilization scenarios provide the two carbon budgets used in this analysis. The Immediate action-450 scenario provides the carbon budget associated with reasonably high chance of limiting the temperature increase to below 2 ^{o}C (the 450-ppm budget). Similarly, the Immediate action-500 scenario provides the carbon budget associated with an even chance of meeting the 2 ^{o}C target (the 500-ppm budget).

Considering our original estimates of the carbon impact of increased wellbeing in all four regions (section 5.1), which were based on the baseline no-action scenario, those two carbon budgets could be exceeded by as much as two and a half times (i.e. a gap of 1,003 $GtCO_2$) and about two times (i.e. a gap of 856 $GtCO_2$) by mid-century, respectively. These gaps reveal the extent of the incompatibility between wellbeing enhancement and climate stabilization efforts at prevailing decarbonisation rates and state of knowledge and technology.

This section presents all gaps between the two carbon budgets and the estimated additional carbon emissions (*projected CO_2 emissions*) associated with future improvements in human wellbeing in each of the four selected regions by 2050, based not only on the baseline no-action scenario but also on the three climate policy scenarios discussed in section 5.2. Table 13 depicts the regional and overall gaps compared to the 450-ppm budget and Table 14 those compared to the 500-ppm budget. An extended assessment is presented in Appendix F, wherein the OECD90 region is also included.

Table 13 – Wellbeing emissions shortfall by 2050 per emissions scenario compared to the 450-ppm budget.

Region/ Scenario	**Immediate action-450 (budget)**	**Gap in No-action scenario**		**Gap in Delayed action-500 scenario**		**Gap in Action as of 2020-500 scenario**		**Gap in Action as of 2020-450 scenario**	
		at least	up to	at least	up to	at least	up to	at least	up to
ASIA	421	396	771	207	484	170	429	82	296
MAF	112	51	71	23	40	4	17	(9)	3
LAM	48	32	78	6	35	(8)	13	(11)	8
EIT	75	40	83	10	40	2	29	(8)	15
Total 4 regions	**655**	**519**	**1,003**	**245**	**598**	**168**	**488**	**54**	**321**
Budget exceeded by (times)			**2.5**						**1.5**

Table 14 – Wellbeing emissions shortfall by 2050 per emissions scenario compared to the 500-ppm budget.

Region/ Scenario	**Immediate action-500 (budget)**	**Gap in No-action scenario**		**Gap in Delayed action-500 scenario**		**Gap in Action as of 2020-500 scenario**		**Gap in Action as of 2020-450 scenario**	
		at least	up to	at least	up to	at least	up to	at least	up to
ASIA	527	291	665	101	378	64	323	(24)	190
MAF	128	35	55	7	24	(12)	1	(25)	(13)
LAM	57	22	68	(4)	25	(17)	3	(21)	(2)
EIT	91	24	67	(6)	24	(13)	14	(23)	(0)
Total 4 regions	**803**	**372**	**856**	**98**	**451**	**21**	**341**	**(93)**	**174**
Budget exceeded by (times)			**2.1**						**1.2**

By analyzing the corresponding shortfalls in the alternative scenarios, we can further assess whether higher decarbonisation rates would reduce the incompatibility between wellbeing enhancement and climate stabilization targets in individual regions where improvements are needed, as well as in all such regions combined.

In ASIA, the incompatibility would likely persist even at much deeper decarbonisation rates, given the shortfalls seen in all three alternative scenarios considered. Only in the lower range of the projections under the most stringent of the climate scenarios considered, the Action as of 2020-450, and considering the less stringent budget (500-ppm budget) could the gap be fully closed.

Conversely, in the other three regions, there could be compatibility between the two efforts at much deeper decarbonisation rates, in particular under the most stringent of the climate scenarios considered, the Action as of 2020-450. Moreover, there is a very small chance that LAM and EIT could afford to delay the start of new climate policies and actions until 2030 and still be able to increase its wellbeing without compromising their corresponding 500-ppm budgets.

Meeting energy needs and enabling the achievement of higher well-being in all four regions combined could prove incompatible with climate stabilization even at higher decarbonisation rates, considering that the estimated carbon budget associated with a reasonably high chance of limiting the temperature increase to below 2 ^{o}C (the 450-ppm budget) could still be exceeded by up to 321 Gt CO_2 (Table 13). Except for, possibly, in the lower range of the projections, under the most stringent of the climate scenarios considered, the Action as of 2020-450, and considering the less stringent budget (500-ppm budget) (Table 14).

6. Analysis of results and recommendations

The results presented above in chapter 5 indicate that even with higher decarbonisation rates associated with the adoption of new policies and actions associated with reasonably high chances of meeting the 2 ^{o}C target, i.e. reaching GHG concentrations at roughly 450 ppm CO_2eq in 2100, starting in 2020, emissions associated with achieving higher levels of collective well-being in all four regions where improvements are still needed, which represent 78 percent of the global population, could still exceed the estimated carbon budgets associated with reasonably high and even chances of limiting the temperature increase to below 2 ^{o}C. This impact would be even greater for lower temperature increase levels.[102]

As such, this study showcases the potential incompatibility between efforts towards bridging the energy divide while enabling the achievement of higher collective wellbeing and those associated with climate stabilization. This is primarily the case in ASIA, where new climate policies would likely have to be adopted before 2020 and/or even more stringent policies and actions than those associated with reasonably high chances of meeting the 2 ^{o}C target, i.e. of reaching GHG concentrations at roughly 450 ppm CO_2eq in 2100, would be required.

In the other three regions, there could be compatibility between the two efforts if new climate policies and actions associated with reasonably high chances of meeting the 2 ^{o}C target, i.e. of reaching GHG concentrations at roughly 450 ppm CO_2eq in 2100, were adopted as of 2020.[103] Moreover, LAM and EIT could potentially afford to delay the start of new climate actions until 2030 and still remain within their less stringent budgets (the 500-ppm budget) should their future energy elasticities equate to those in the lower bound of the projections, i.e. increasing from 1.24 to at least 1.30 and from 1.23 to at least 1.26 from 2011 through 2020 and remaining constant thereafter, respectively.

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[102] As noted in section 2.3.1, in the Paris Agreement signed in 2015, Parties agreed to revise the target to "well below 2 ^{o}C" and to pursue further efforts aiming at limiting temperature increase to below 1.5 ^{o}C (UNFCCC, 2015).

[103] However, should MAF improve its capacity to generate greater produced capital and human capital, and thereby increase its wellbeing beyond 6 percent by mid-century, there would likely be incompatibility issues similar to those seen in ASIA.

Based on the results obtained, this chapter discusses them, while attempting to provide answers to the four pressing questions presented at the beginning of this thesis (see Introduction) and some recommendations.

6.1. Answering question number 1: how much energy consumption, and its corresponding CO_2 emissions, would be needed to bridge the energy divide and enable the achievement of higher levels of collective wellbeing?

According to the assessment carried out, meeting the urgent energy needs while enabling the achievement of higher levels of human wellbeing in all four regions where improvements are still needed,[104] representing 78 percent of global population (based on 2010 data), would require at least 1,174 $GtCO_2$ and as much as 1,658 $GtCO_2$ of cumulative emissions between 2011 and 2050, at current decarbonisation rates and state of knowledge and technology. This range is equivalent to annual emissions of about 30 to 43 $GtCO_2$, which are much higher than the recent (2013) level for all four regions combined of about 20 $GtCO_2$ (WORLD BANK, 2017).

6.2. Answering question number 2: Would the existing carbon budgets be affected?

The estimated cumulative emissions associated with bridging the energy divide while enabling the achievement of higher levels of wellbeing in all four regions could exceed the overall 450-ppm budget by up to two and a half times (i.e. a gap of 1,003 $GtCO_2$) by 2050, assuming prevailing technologies and decarbonisation rates. Similarly, the overall 500-ppm budget could be exceeded by up to two times (i.e. a gap of 856 $GtCO_2$) by the same time.

The carbon impact would be even greater should lower temperature increase levels be pursued. Given the recent adoption of the Paris Agreement, current climate stabilization efforts are already due to be strengthened with a view to keeping global temperature rise this century well below 2 ^{o}C above pre-industrial and potentially even

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[104] As noted in section 4.3, the OECD-90 region is not included in the analysis as it is not as an area where relevant improvements in wellbeing are needed.

below 1.5 ^{o}C, as noted in section 2.3.1.[105]

6.3. Answering question number 3: If so, what part(s) of the world would be mostly at risk?

Based on the assessment carried out, ASIA and MAF are the regions with the greatest need for improvement in collective wellbeing in terms of per capita IWI. As discussed in section 2.2, they also represent the areas were the so-called “energy poor” dwell in and where most of the population growth is expected to take place by mid-century, almost 2 billion people.

By 2050, ASIA alone is expected to represent over half of the total population, with over 4.4 billion people, while MAF would entail just over 1 billion people. This difference partially explains why ASIA alone accounts for over 60 percent of the estimated additional energy needed and up to 72 percent of the associated carbon emissions, making it by far the most critical area where efforts to reduce the carbon impact of the necessary improvements in human wellbeing would be most needed.

The estimated carbon budgets associated with reasonably high (450-ppm) and even (500-ppm) chances of limiting the temperature increase to below 2 ^{o}C in ASIA could be exceeded by almost three times (i.e. a gap of 771 $GtCO_2$) and by over two times (i.e. a gap of 665 $GtCO_2$), respectively, by mid-century.

6.4. Answering question number 4: what needs to be done to bridge the energy divide and increase wellbeing while staying within existing carbon budgets?

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[105] ROGELJ *et al.* (2015) provide estimated pathways associated with limiting average global temperature warming to below 1.5 °C by 2100.

Based on the findings obtained, adoption of new climate policies and mitigation actions beyond those already in place in 2010 would be critical to be able to bridge the energy divide while enabling the achievement of higher levels of collective wellbeing without exceeding the existing carbon budgets associated with meeting the prescribed 2 ^{o}C target.

This applies in particular to ASIA, where, for instance, the adoption of new policies and actions associated with reasonably high chances of meeting the 2 ^{o}C target, i.e. reaching GHG concentrations at roughly 450 ppm CO_2eq in 2100, starting in 2020, would reduce the upper range of the gap compared to the 450-ppm budget from 771 to 296 $GtCO_2$ and the lower range from 396 to 82 $GtCO_2$ (Table 13). It would be a significant reduction. However, in order to fully close the gap, either such new policies and actions would have to be adopted before 2020 or more stringent new policies and actions, including higher deployment levels of low-carbon, carbon dioxide removal (CDR), and/or negative emissions technologies, would likely have to be adopted starting in 2020.

Meanwhile, MAF, EIT and LAM would also have to adopt new policies and actions associated with high chances of meeting the prescribed 2 ^{o}C target, i.e. reaching GHG concentrations at roughly 450 ppm CO_2eq in 2100, beyond those already in place (as of 2010), starting in 2020, in order to ensure full mitigation of the carbon impact associated with bridging the energy divide and achieving higher levels of collective wellbeing.

It is worth noting that these three regions would enjoy very different improvements in wellbeing, as discussed in section 5.1, despite having somewhat similar carbon impacts. LAM and EIT would achieve increases of 50 and 27 percent, respectively, with LAM moving out of energy poverty levels before mid-century and EIT improving its already decent level of energy consumption rate even further. Meanwhile, MAF would see an increase of only 6 percent in its level of collective wellbeing and an increase of up to 63 GJ/capita in its average primary energy consumption rate by mid-century,[106] neither of which indicates that the region would be moving much further out of the energy poverty levels.

6.5. Recommendations

Meeting future energy needs with deployment of low-carbon energy technologies would allow higher levels of collective wellbeing measured in terms of IWI to be reached while maintaining low associated emissions, since it could significantly reduce the impact on natural capital, otherwise driven by fossil fuels extraction. This approach would also help unlock MAF's ability to reach even higher levels of collective wellbeing since investments in clean technologies would boost produced capital and in turn yield much higher levels of IWI. Moreover, investments in low-carbon energy technologies would improve energy security and reduce the risk of price fluctuations for net oil-importing countries in the region (e.g. Bahrain, Israel, Jordan, Morocco, and South Africa), thereby alleviating the challenge of expanding energy access (OECD/IEA, 2010) without significant conflicts with climate stabilization efforts.

However, in order to achieve higher deployment rates of cleaner technologies in these regions investments would have to be scaled up significantly. Even though ASIA leads global investments in renewables with an estimated USD 161 billion in 2015 (IRENA, 2017) and MAF has been attracting increased levels of investment, having summed USD 12 billion in 2015 (IRENA, 2017),[107] these levels of investments fall considerably short of those needed to meet climate goals (IRENA, 2016). Solar and wind power have dominated the share of investments in these regions, as well as globally (IRENA, 2017). While there is still significant potential for further deployment of renewables in the power sector, an untapped potential remains for the use of renewables for heating and cooling in buildings and industry as well as for transportation. Together, these end-user sectors account for a large portion of global

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[106] As noted in section 2.2, recent studies suggest that societies typically require an annual per capita primary energy consumption rate above 50 GJ (SMIL, 2010a) or 63 GJ (SPRENG, 2005) to be able to achieve decent living standards.

[107] These investments include all asset classes, including asset finance, corporate R&D, government R&D, public markets, reinvested equity, small distributed capacity and venture capital, private equity (IRENA, 2017).

energy use and about 60 percent of energy-related CO_2 emissions (IEA, 2015b).

Yet, additional capital commitments face two important barriers in these areas: high-perceived investment risks (e.g. political, credit, currency, and power-offtake risks) and lack of local capacity and resources for project development (IRENA, 2017). So as to overcome these barriers, well-structured financial frameworks alongside tailored energy policies to local circumstances and to optimize synergies, such as between the power and end-user sectors, should be sought out.

Moreover, the levels of deployment of low-carbon energy technologies that would be needed to fully mitigate the carbon impact associated with increased wellbeing, in particular in ASIA, may not be realistic in the timeframe under consideration. While there has been an increased deployment of low-carbon energy technologies, the transition away from the current, long-established energy systems relying overwhelmingly on fossil fuels, or what could be called the 5th great energy transition, following the timeline presented in section 2.1, is a process that is still unfolding and is not expected to be completed before mid-century. According to mainstream conceptions, the current energy transition will invariably take decades to occur based on historical record and recent advances (FOUQUET, 2010; GRUBLER, 2012; SMIL, 2006, 2010a and 2016).[108]

In light of these considerations, without broader, concerted collaboration between advanced countries and the rest of the world, it will be very hard for these regions to transition to the low-carbon and low energy-intensive pathways that would allow them to meet pressing energy needs and secure higher levels of human wellbeing without harming the environment or weakening social conditions that could, otherwise, compromise the wellbeing of their future generations. As such, in order to make the pursuit towards higher collective wellbeing compatible with climate stabilization, advanced countries may need to go beyond technology transfers and financial assistance and face the burden of reducing their own emissions even further to make room for

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[108] SMIL (2006) outlines some of the underlying reasons for the expected timing, namely: the scale of the shift; the lower energy density of the replacement fuels; the substantially lower power density of renewable energy extraction; intermittency of renewable flows; and uneven distribution of renewable energy resources.

increased emissions needed to secure higher collective wellbeing in the rest of the world.

Nevertheless, as shown in Appendix F, even if new climate policies and mitigation actions associated with reasonably high chances of meeting the 2 °C target, i.e. reaching GHG concentrations at roughly 450 ppm CO_2eq in 2100, were adopted in all four regions where improvements are still needed as well as in advanced countries (OECD90 region) in 2020, emissions associated with meeting the urgent energy needs while enabling the achievement of higher levels of collective wellbeing, could still exceed the estimated carbon budgets associated with reasonably high and even chances of limiting the temperature increase to below 2 °C by almost one and a half times (i.e. a gap of 397 $GtCO_2$) and by over one time (i.e. a gap of 198 $GtCO_2$), respectively, by mid-century.

Given the scale of the overall gaps, to make room for increased emissions needed to secure higher wellbeing in the rest of the world, advanced countries would likely need to achieve very low or even net zero CO_2 emissions in key energy-dependent sectors. Such a feat would likely require deployment of mitigation strategies beyond those aiming to achieve carbon neutrality already in 2020. As noted in section 2.3.2, there is a range of negative emissions technologies at various stages of development under consideration worldwide. However, concerns have been raised with regard to the safety of betting on the use of negative emissions after mid-century to avoid dangerous climate change (e.g. FUSS *et al*., 2014),[109] which would make the reliance on its use already in the short- and mid-term even more questionable. The feasibility of large-scale negative emissions programs has yet to be proven and will require significant technological progress (SMITH and TORN, 2013), considering that numerous resource implications associated with the widespread implementation of these technologies need to be satisfactorily addressed and associated costs reduced to acceptable levels (FUSS *et al*., 2014; SMITH *et al*., 2016; UNEP, 2016).[110] [111]

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[109] However, as noted in section 2.3.3, these types of mitigation strategies, in particular BECCS, are most widely selected in the second half of the 21st century of pathway scenarios in IAMs to deliver a medium chance of meeting the 2 °C target, let alone for lower targets (KRIEGLER *et al*., 2013; FUSS *et al*., 2014; SMITH *et al*., 2016).

[110] Several non-economic impacts include those related to land requirements, energy demands, water and nutrient uses, and biophysical climate impacts (see FUSS *et al*., 2014; SMITH *et al*., 2016; UNEP, 2016).

Clearly, other solutions would need to be put in place simultaneously. Policies targeting changes in behavior and energy consumption patterns have been recommended as an important supporting measure to reducing energy-related emissions in advanced countries (SMIL, 2010; ROY *et al.*, 2012; NEUVONEN *et al.*, 2014; UNEP, 2016), since they can often result in relevant energy savings (ALLCOTT AND MULLAINATHAN, 2010; EHRHARDT- MARTINEZ *et al.*, 2010; EEA, 2013).[112]

Consumer activities influencing energy consumption directly (e.g., home energy use and personal travel) roughly account for more than 40 percent of total primary energy consumption (GRUBLER *et al.*, 2012; ROY *et al.*, 2012).[113] As such, promoting widespread use of energy efficient appliances and of smart meters in homes, for instance, as well as encouraging the switch to electric cars, or simply to walking or cycling instead of driving for short trips are at most times realistic and feasible changes that can reduce energy consumption and thereby help achieve emission reductions, primarily in advanced countries. Some may point out to the fact that the total useable autonomous energy that batteries can typically store is an important limiting factor to the widespread switch to electric cars, as noted in (KHAN RIBEIRO *et al.*, 2012; HARDMAN *et al.*, 2016).[114] [115] However, as demonstrated in KHAN AND KOCKELMAN (2012) and JAKOBSSON *et al.* (2016), replacing second cars in two-car households with electric cars would only require small adaptations in driving habits.[116]

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[111] According to SCOTT et al. (2012), the capital cost of five to ten full-size demonstration plants of BECCS or CCS would require an investment of approximately US$5 to 10 billion. SMITH *et al.* (2016) also note that the cost of infrastructure to transport CO_2 from BECCS production areas to storage locations has yet to be further evaluated.

[112] A literature review indicated that behavioral measures across the EU could result in 5 to 20 percent reduction in energy consumption (EEA, 2013). According to a meta- analysis involving 29 studies, feedback-induced energy savings could range from 0.5 to 13 percent compared to previous levels (EHRHARDT- MARTINEZ *et al.*, 2010). According to studies reviewed by ZVINGILAITE AND TOGEBY (2015) energy savings could reach up to 18 percent as a result of initiatives that provide feedback on consumption to energy users.

[113] Home energy includes: space heating, other appliances and lighting, water heating, refrigeration and air conditioning. Personal travel refers to short distance travel by automobiles and trucks, as well as long distance travel by air.

[114] Existing electric grids already provide for the most critical part of the infrastructure needed for electric cars (KHAN RIBEIRO *et al.*, 2012).

[115] Although recently launched high-end (US$70,000-105,000) battery electric cars have advertised driving ranges of 270 miles (434 km), more affordable ones (US$30,000-40,000) have driving ranges below 100 miles (160km) (HARDMAN *et al.*, 2016).

[116] The autonomous range limitations may be circumvented by the fact that trips can be shifted between

Another lifestyle choice that has significant implications for energy consumption is diet. The difference between the energy inputs for plant- and meat-based meals may exceed a factor of ten (ROY *et al.*, 2012).[117] Therefore, the reduction in consumption of animal-based protein clearly translates into lower energy consumption and related emissions. The difference between animal-based and vegan diets equals 19.6 GJ per year for a family of four in Sweden, 24.4 GJ per year for a similar family in Australia, and 13.8 GJ per year in the United Kingdom (ROY *et al.*, 2012). Similarly, incentives towards increased consumption of organic products and reduced food waste could make further contributions. Unlike conventional agriculture production, organic farming foregoes energy intensive fertilizers, chemicals, and concentrated feed, thus resulting in lower overall energy use (ZIESEMER, 2007; cited in ROY *et al.*, 2012). Moreover, the amount of food that is not consumed and is thrown away or wasted through food preparation represents another area of significant impact on energy consumption. According to CUÉLLAR and WEBBER (2010), the energy embedded in wasted food in the United States represented approximately 2 percent of the country’s energy consumption in 2007, for example.

Achieving reductions in energy-related emissions through changes in behavior and energy consumption patterns can provide multiple benefits like improved health and nutrition and lower local pollution, without reducing socio-economic status (ROY *et al.*, 2012). As such, it provides for an effective strategy not only to help accelerate the transition to low-carbon societies, but also to achieve more sustainable ones. Yet, behavioral change is dependent on the interplay between degrees of public awareness and understanding needed for individual decision-making and incentives (e.g. policies) and means (e.g., infrastructure, technology) needed for action, as suggested in NEUVONEN *et al.* (2014).

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the two cars. Also, because multi-car households are likely to have higher income, they are more likely to afford the higher purchase price of electric cars JAKOBSSON *et al.* (2016).

[117] The production of 1 kcal of grain and animal proteins requires about 2.2 kcal and 25.0 kcal of fossil energy, respectively (PIMENTEL AND PIMENTEL, 2003).

7. Final remarks

This final chapter presents highlights the main contributions and policy implications of this study and provides suggestions on how the assessment proposed in this thesis could be further improved and/or expanded in future studies.

7.1. Contributions and policy implications

The results obtained in this study corroborate to recent calls for urgent action to avoid higher emission reduction rates needed in the future and lock-in effects of carbon and energy intensive infrastructure (CLARKE *et al.*, 2009; DESSENS *et al.*, 2014; JAKOB *et al.*, 2012; KNUTTI *et al.*, 2016; KRIEGLER *et al.*, 2013; ROEGLJ *et al.*, 2016b). Higher emission reduction rates would entail even higher mitigation costs. Similarly, infrastructure lock-in would result in expensive unusable assets and hinder the transition to more efficient energy consumption patterns (UNEP, 2015 and 2016).[118]

The main policy implication of this study, however, is the demonstration of the likely incompatibility between climate stabilization and energy equity and wellbeing enhancement policies and actions. A finding that is bound to raise significant concern as it showcases the extent to which climate action can affect and/or be affected by efforts to achieve other important sustainable development goals (SDGs).[119] Interestingly, this somewhat contrasts with the findings in the latest UNEP Emissions Gap Report (UNEP, 2016), wherein no potential conflict is identified between expanded energy consumption and climate objectives within the SDG directly associated with bridging the energy divide, SDG7 ("Ensure access to affordable, reliable sustainable and modern energy services for all"). According to their findings, achieving SDG7 will not have material implications for global emissions.[120] Most likely this discrepancy results from the fact that these findings refer primarily to increasing access to basic levels in areas of

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[118] Investment in conventional power generation remains strong; oil and gas alone still represent the largest single category of global energy investment, accounting for over 45% of the total (IEA, 2016).

[119] Even though improving collective wellbeing is not specifically prescribed by any SDG, improvements in several different aspects of human wellbeing and living conditions that would allow it to happen are.

[120] They cite the findings from the International Energy Agency, which indicate that achieving universal access to modern energy services would result in negligible increases in global greenhouse gas emissions (IEA, 2013).

extreme poverty and not to a broader effort of bringing energy access to levels beyond those associated with minimum living conditions, as was intended in the present study.

Another important policy implication is the finding that advanced countries may need to face the burden of reducing their own emissions even further to make enough room for increased emissions needed to secure higher collective wellbeing in the rest of the world. However, because neither the current transition away from the long-established energy systems relying overwhelmingly on fossil fuels that is required to achieve the needed levels of deployment of low-carbon energy technologies nor the technological progress needed for large-scale use of negative emissions technologies are expected to be completed before mid-century, changes in lifestyle choices such as those associated with home energy use, private travel, and diet would probably be critical for advanced countries to reduce their own emissions even further.

Promoting behavioral change in terms of consumer purchases and lifestyle habits is actually embedded within several Sustainable Development Goals (SDGs) and specifically prescribed by SDG12 (“Ensure sustainable consumption and production patterns”).[121] SDG12 identifies key areas where changes to existing patterns can be made and establishes specific targets such as to halve per capita food waste by 2030. Other targets focus on achieving sustainable management and efficient use of natural resources, reducing waste generation, encouraging companies to adopt sustainable practices and report on them, educating consumers about sustainable lifestyles, promoting green public procurement, as well as rationalizing inefficient fossil fuel subsidies that encourage wasteful consumption (UNGA, 2015).

With advanced countries leading the way in making the necessary changes in consumption patterns and behaviors towards a more sustainable lifestyle, there might be a chance for rest of the world to secure higher collective wellbeing by mid-century, without compromising climate stabilization efforts. By doing so, advanced countries would also be leading the way up the evolutionary ladder, according to ancient Indian

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[121] In September 2015, world’s governments adopted a set of 17 Sustainable Development Goals (SDGs) and 169 associated targets, as included in the 2030 Agenda for Sustainable Development (UNGA, 2015), to follow up the Millennium Development Goals (MDGs). The SDGs came into force on January 1st, 2016.

perspectives on wellbeing (discussed in section 3.1), i.e. gradually transitioning out of the material individualism aligned with the prevailing hedonistic or utilitarian approach to wellbeing through degrees of the collectivistic or eudaimonic approach to it, towards spiritual collectivism, at which point wellbeing is only perceived as being achieved for oneself when everyone else on the planet has also achieved it.

Delays in acknowledging and tackling the climate stabilization and wellbeing enhancement dilemma are bound to leave recently renewed commitments to lower global temperature increases adrift. Meanwhile, early impacts of climate change will likely widen the existing energy and well-being divide, given that the most climate-vulnerable areas are also those in greater need of improvements in energy access and well-being. More than ever, the relationship between energy consumption and human wellbeing, beyond its economic dimension, needs to be better understood.

While a lot more research is still needed, this thesis sought to contribute to the emerging knowledge base by: selecting a proxy for human wellbeing that encompasses not only the economic and social dimensions of human development, but also its environmental dimension, within a single value; and, ultimately, providing an indication of whether meeting urgent energy needs while enabling the achievement of higher levels of collective wellbeing would be consistent or conflict with climate stabilization targets.

In order to accomplish this, a quantitative assessment based on a linear model on log-log form was conducted to examine the relationship between energy consumption and human wellbeing across one hundred and eighteen countries over the period from 1990 to 2010, using the Inclusive Wealth Index (IWI) as a proxy for human wellbeing selected from existing alternative aggregate indicators to GDP. While the correlations observed could not determine whether there is causality between the two variables, they provided sufficiently reliable data to derive a range of future wellbeing elasticities of energy consumption, which were used to estimate the additional primary energy consumption levels that would be required to meet urgent energy needs while enabling the achievement of higher levels of collective wellbeing in all regions where improvements are still needed.

By applying CO_2 emission intensities from the no-policy baseline scenario of the integrated assessment model MESSAGE to the estimated primary energy consumption levels, the associated carbon emissions were also estimated, assuming no new climate policies (no-action scenario) and given prevailing technologies and decarbonisation rates. In order to determine whether these emissions would affect existing carbon budgets, they were compared to two emissions pathways associated with the 2 ^{o}C climate stabilization target from the same integrated assessment model. Alternative scenarios (action scenarios Action as of 2020-500, Action as of 2020-450, and Delayed action-500) were also considered, wherein new climate policies are taken into consideration to determine whether and how some gaps could be closed.

7.2. Suggestions for future research

The estimates provided in this study were compared to previous quantification efforts in the literature that used HDI or its components as proxy for human wellbeing (see Appendix E). The results obtained indicated primary energy consumption levels and of CO_2 emissions higher than those obtained in the very few previous studies with similar quantifications, namely PASTERNAK (2000) and UGURSAL (2014) for energy and COSTA *et al.* (2011) and LAMB AND RAO (2015) for CO_2 emissions. However, the assessment proposed in this study has several limitations and significant room for further improvement.

The selected indicator used as proxy for human wellbeing is deemed to be fraught with methodological limitations (THIRY AND ROMAN, 2014). Therefore, future research should consider using different alternative indicators to GDP as more data points become available for them (increased number of years and/or countries covered), such as the Sustainable Society Index (SSI) and the Legatum Prosperity Index.

The assessment could also be complemented by a similar analysis using final energy consumption data. A comparison of the two sets of results would help identify the carbon impact associated with how energy is used, and not only that associated with the primary sources, and provide better energy conservation and/or efficiency policy recommendations. This would also allow for a more direct comparison with the estimates provided in LAMB AND RAO (2015), in particular with regard to Africa.

The region aggregation could also be revised to allow for more in-depth analysis of specific regions. One suggestion would be to apply the latest set of harmonized regions developed for the LIMITS project, the so-called ten plus (10+1) “super regions”. Each of these regions is comprised of countries with relatively similar energy system structures and requirements (LIMITS Database, 2016), and is categorized as follows:

- AFRICA = countries of Sub-Saharan Africa
- CHINA+ = countries of centrally-planned Asia, primarily China
- EUROPE = countries of Eastern and Western Europe (i.e., the EU27)
- INDIA+ = countries of South Asia, primarily India
- LATINAM = countries of Latin America and the Caribbean
- MIDDLEEAST = countries of the Middle East
- NORTHAM = countries of North America, primarily the USA and Canada
- PACOECD = countries of the Pacific OECD
- REFECON = countries from the Reforming Economies of Eastern Europe and the Former Soviet Union
- RESTASIA = other countries of Asia
- RESTWORLD = countries not elsewhere classified

This disaggregation would allow for a more detailed assessment within ASIA and MAF. It would, thus, allow for further investigation of the energy needs, as well as the needs for improvements in wellbeing and the potential carbon impact of meeting those needs in specific countries like China, India, and South Africa, as well as specific sub-regions like all other Asian countries besides China and India and Sub-Saharan Africa.

Moreover, other climate action scenarios could be included in the assessment, such as a scenario that specifically reflects all the latest climate pledges outlining carbon mitigation targets based on post-2020 action (INDCs). As this work was being developed, one hundred and sixty two INDCs had been submitted to the UNFCCC (UNFCCC, 2017).

Lastly, scenarios associated with more stringent policies and actions aimed at meeting lower temperature increase levels by 2100 (e.g. up to 1.5 ºC) could also be included, as they become available. ROGELJ *et al.* (2015) provide estimated pathways associated with limiting average global temperature warming to below 1.5 °C by 2100 on a global level. The IPCC is scheduled to provide a special report on the impacts of global warming of 1.5 ºC above pre-industrial levels and related emission pathways in 2018 (IPCC, 2016), which will likely include regional pathways.

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Appendix A – Table of selected studies on energy consumption, GDP growth, and CO_2 emissions

Table A 1 - Selected studies on energy consumption, GDP growth, and CO_2 emissions.

Studies	Period	Countries	Causality relationship	Methodology
KRAFT AND KRAFT (1978)	1947–1974	United States (U.S.)	Y → EC	Granger causality test
AKARCA AND LONG (1980)	1947–1972	United States	No causality	Granger causality test
YU AND HWANG (1984)	1947–1979	United States	No causality	Granger causality test
YU AND CHOI (1985)	1950–1976	Poland, UK, US, Korea, Philippines	Y ↔ EC, Y → EC, EC → Y	Granger causality test
EROL AND YU (1987)	1950–1982	Canada, France, UK, Italy, Japan, Germany	No causality, Y → EC, EC → Y	Granger causality test
NACHANE *et al.* (1988)	1950–1985	16 countries	Y ↔ EC	Granger causality test
EBOHON (1996)	1960–1984	Nigeria, Tanzania	Y ↔ EC	
MASIH AND MASIH (1996)	1955–1991	Malaysia, Philippines, Singapore, India, Indonesia, Pakistan	EC → Y, Y → EC, Y ↔ EC	Cointegration, error correction model
MASIH AND MASIH (1998)		Sri Lanka, Thailand	EC → Y	
ASAFU-ADJAYE (2000)	1971–1995	Philippines, Thailand, India, Indonesia (1973-95)	Y ↔ EC, EC → Y	Cointegration and Granger causality based on ECM
SOYTAS AND SARI (2003)	1950–1994	Argentina, Italy, Korea, France, Germany, Japan, Turkey	Y ↔ EC, Y → EC, EC → Y	Johansen multivariate
LEE (2005)	1975–2001	18 developing countries	EC → Y	Panel cointegration, Granger causality based on ECM
LEE AND CHANG (2005)	1954–2003	Taiwan	EC→Y	Johansen–Juselius, Granger causality-VECM
WOLDE-RUFAEL (2005)	1971–2001	19 countries in Africa	Y→EC (Algeria, Congo DR, Egypt, Ghana, Ivory Coast), EC→Y (Cameroon, Morocco, Nigeria) EC ↔ Y (Gabon, Zambia), No causality (Benin, Congo RP, Kenya,	Toda Yamamoto's Granger causality

Studies	Period	Countries	Causality relationship	Methodology
			Senegal, South Africa, Sudan, Togo, Tunisia, Zimbabwe)	
AL-IRIANI (2006)	1970-2002	6 Gulf countries	Y → EC	Panel cointegration, GMM
LEE (2006)	1960-2001	Germany, UK, Sweden, US, Belgium, Canada, Netherlands, Switzerland, France, Italy, Japan	No causality, Y ↔ EC, EC → Y, Y → EC	Granger causality test
LEE AND CHANG (2007)	1965-2002	22 developed countries, 18 developing countries	Y ↔ EC (developed countries), Y → EC (developing countries)	Panel VARs and GMM
MAHADEVAN AND ASAFU-ADJAYE (2007)	1971-2002	20 energy importers and exporters	EC→Y (in the short run for developing countries)	Panel error correction model
MEHRARA (2007)	1971–2002	11 oil-exporting countries	Y → EC	Panel cointegration, Granger causality-VECM
SOYTAS *et al.* (2007)	1960-2004	United States	EC → C	EKC hypothesis, Granger causality test
AKINLO (2008)	1980-2003	Sudan, Zimbabwe, Gambia, Ghana, Senegal, Cameroon, Cote d'Ivoire, Kenya, Nigeria, Togo	Y → EC, Y ↔ EC, No causality	ARDL bounds test
ASHGAR (2008)	1971–2003	Bangladesh, Nepal, Pakistan	Y → EC	
CHIOU-WEI *et al.* (2008)	1954-2006	Asian countries and USA	No causality (USA, Thailand, South Korea), Y → EC (Philippines, Singapore), EC → Y (Taiwan, Hong Kong, Malaysia, Indonesia)	Granger causality
CHONTANAWAT *et al.* (2008)		30 OECD countries and 78 non-OECD countries	EC→Y in 70% of OECD countries and 46% of non-OECD countries (69% of high-HDI countries, 42% od mid-HDI countries, and 35% low-HDI countries)	Hsiao's version of Granger causality test
HUANG *et al.* (2008)	1972–2002	Low-income countries, Middle-income countries, High-income countries	No causality (low income), Y → EC (positively in middle income, negatively in high income)	Panel VAR model, GMM-SYS approach
LEE AND CHANG (2008)	1971–2002	16 Asian countries	EC → Y (in the long-run)	Panel cointegration and Panel ECM
LEE *et al.* (2008)	1960-2001	22 OECD countries	EC↔Y	Panel cointegration, panel VEC

Studies	Period	Countries	Causality relationship	Methodology
				model
APERGIS AND PAYNE (2009)	1971-2004	6 Central American countries	C ↔ Y, EC→ C, Y→ C, Inverted U-shaped curve	EKC hypothesis, panel VECM
ODHIAMBO (2009)	1971–2006	Tanzania	EC→Y	ARDL bonds test, Granger causality-VECM
SOYTAS AND SARI (2009)	1960-2000	Turkey	C↔ EC (in the long-run)	Granger causality test
ZHANG AND CHENG (2009)	1960-2007	China	Y→ EC, EC→ C	Toda-Yamamoto method
APERGIS AND PAYNE (2010)	1980–2005	9 Latin American countries	EC → Y	Pedroni Panel cointegration, error correction model
BELKE *et al*. (2010)	1981-2007	25 OECD countries	Y ↔ EC	Granger-causality
COSTANTINI AND MARTINI (2010)	1978–2005	71 countries	Different causality relations	
KAHSAI *et al*. (2010)	1980–2005	19 African countries	Y ↔ EC	
OZTURK *et al*. (2010)	1971-2005	51 countries (3 income groups)	Y and EC cointegrated for all 3 groups, low-income: short-run causality: Y→EC, middle-income: EC↔Y, no strong relation found	Pedroni (1999) and Pedroni (2001) panel data analysis
PAO AND TSAI (2010)	1971-2005	BRIC countries	EC↔Y	Granger causality with VAR and ECM
CHANG AND CARBALLO (2011)	1971-2005	20 Latin American and Caribbean countries	EC→Y (Brazil, Costa Rica, Honduras, and Paraguay), Y→EC (Jamaica and Venezuela), and EC ↔ Y (Colombia, Peru, and Uruguay)	Phillips and Perron tests, Granger causality with VECM and VAR
APERGIS AND PAYNE (2012)	1990-2007	80 countries	EC↔Y	Panel error correction model, panel analysis
AROURI *et al*. (2012)	1981-2005	12 MENA countries	EC ↔ C (in the long-run)	Panel unit root tests and cointegration
AKKEMIK AND GOEKSAL (2012)	1980-2007	79 countries	EC↔Y in 57 countries (19 developed and 38 developing or EIT)	Modified Granger causality technique
LEE (2013)	1971-2009	19 G20 countries	EC → C	Panel cointegration model
OMRI (2013)	1990-2011	14 MENA countries	EC↔Y, EC→C, C↔Y	Cobb-Douglas function, GMM method
OMRI AND KAHOULI (2013)	1990-2011	65 countries	EC↔Y, EC→Y	Granger causality test
KHAN *et al*. (2014)	1975-2011	low, middle, high income non-OECD	low and middle income, as well as MENA countries: Y→EC, high	Im-Pesaran–Shin unit root tests, Pedroni's cointegration test,

Studies	**Period**	**Countries**	**Causality relationship**	**Methodology**
		and OECD, MENA	income: Y≠EC	Seemingly Unrelated Regression test
OMRI *et al*. (2014)	1990-2011	54 countries	C→ Y, Y ↔ C: MENA countries	Cobb-Douglas function, GMM method
SABOORI *et al*. (2014)	1960-2008	OECD	EC ↔ C	VAR-Granger causality test
TANG AND ABOSEDRA (2014)	2001-2009	24 MENA countries	EC→ Y	GMM estimator
YILDRIM *et al*. (2014)	1971-2011	9 countries	EC→Y for Turkey	Bootstrapped autoregressive metric causality
NASREEN AND ANWAR (2014)	1980-2011	15 Asian countries	Y ↔ EC	VECM-Granger causality test

Notes: → denotes unidirectional causality, ↔ denotes bi-directional causality or feedback hypothesis, ≠ denotes indifference or neutrality hypothesis, EC = per capita energy consumption, Y = per capita real or nominal GDP, C = per capita carbon dioxide emissions, J-J = Johansen-Juselius, ARDL = Autoregressive distributed lags, T-Y = Toda– Yamamoto causality, VAR = Vector autoregressive, VECM = Vector autoregressive.

Source: Updated and adapted from OZTURK, 2010, CHEN *et al*. (2012), AKKEMIK AND GOEKSAL (2012), OMRI (2013), and QUEDRAGOGO (2013).

Appendix B – Table of key alternative indicators to GDP.

Table B 1 - Key alternative indicators to GDP.

Alternative Indicators	Year introduced	Approach to GDP	EcD	SD	EnD	Number of countries covered	Period covered (years)	References
Measure of Economic Welfare (MEW)	1972	*adjusting*	✓	✓		1	36	NORDHAUS AND TOBIN, 1972
World Values Survey (WVS)	1984	*replacing*	✓	✓		80	33	DIENER AND SUH, 1997
Index for Sustainable Economic Welfare (ISEW)	1989	*adjusting*	✓	✓	✓	14	29	DALY AND COBB, 1989
Human Development Index (HDI)	1990	*replacing*	✓	✓		188	24	UNDP, 1990, 2010, 2013, and 2015
Genuine Progress Indicator (GPI)	1995	*adjusting*	✓	✓	✓	17	60	ANIELSKI AND ROWE 1999, TALBERTH *et al*., 2007, KUBISZEWSKI *et al*., 2013
Index of Economic Wellbeing (IEWB)	1998	*adjusting*	✓	✓	✓	14	29	OSBERG AND SHARPE, 1998 and 2011
Happy Planet Index (HPI)	2006	*replacing*	✓	✓	✓	151	6	MARKS *et al*., 2006
Sustainable Society Index (SSI)	2008	*adjusting*	✓	✓	✓	151	8	VAN DE KERK AND MANUEL, 2014
The Legatum Prosperity Index	2009	*adjusting*	✓	✓	✓	110	6	LEGATUM INSTITUTE, 2009
Human Sustainable Development Index (HSDI)	2010	*replacing*	✓	✓	✓	188	1	TOGTOKH, 2011
Sustainable Economic Development Assessment (SEDA)	2011	*adjusting*	✓	✓	✓	149	3	BEAL *et al*., 2015
Adjusted Net Savings (ANS)	2012	*adjusting*	✓		✓	144	13	WORLD BANK, 2013
Inclusive Wealth Indicator (IWI)	2012	*adjusting*	✓	✓	✓	116	20	UNU-IHDP AND UNEP, 2012 and 2014
Social Progress Index (SPI)	2013	*supplementing*		✓	✓	133	2	PORTER *et al*., 2016

Note: EcD = Economic Dimension, SD = Social Dimension, and EnD = Environmental Dimension.

Source: Prepared by the author based on data from GOOSSENS *et al*., 2007 and SCHEPELMANN *et al*., 2010, and own research.

Appendix C – Table of key data and calculations.

Table C 1 – Description of key data and calculations.

Data	Description	Sources
Historic data		
Inclusive Wealth Index (IWI) (millions 2005 US$)	Social value of an economy's capital assets (e.g. natural, manufactured, humans, and social), seen as determinants of wellbeing and proxies to its actual constituents. Started with a list of 140 countries in IWR 2014, then eliminated those for which there were no energy consumption data in the World Bank database and arrived to 118 countries. Data provided for years 1990, 1995, 2000, 2005 and 2010 for all countries except for Croatia, Kazakhstan, Kyrgyzstan, Lithuania, Russian Federation, Slovenia, Tajikistan, and Ukraine (1991 data provided instead of 1990) and Czech Republic and Slovakia (1992 data provided instead of 1990). Data for intermediate years were calculated based on compound annual growth rates.	IWR 2014 (UNU-IHDP and UNEP, 2014)
GDP, PPP (constant 2011 international $)	Gross domestic product converted to international dollars using purchasing power parity rates. An international dollar has the same purchasing power over GDP as the U.S. dollar has in the United States. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in constant 2011 international dollars.	World Development Indicators (WORLD BANK, 2016)
Deflators used to convert GDP to 2005 US$	Implicit Price Deflators for Gross Domestic Product	Bureau of Economic Analysis (BEA) (https://bea.gov/itable/
Energy use (EU) (kg of oil equivalent per capita)	Energy use refers to use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport.	World Development Indicators (WORLD BANK, 2016)
Energy consumption (EC)	EC = EU converted from koe into GJ: 1 GJ = 1 koe / 1000 x 41.868	OECD/IEA 2016 (https://www.iea.org/statistics/resources/unitconverter)
Population	Total population is based on the de facto definition of population, which counts all residents regardless of legal status or citizenship--except for refugees not permanently settled in the country of asylum, who are generally considered part of the population of their country of origin. The values shown are midyear estimates.	World Development Indicators (WORLD BANK, 2016)

Data	Description	Sources
CO_2 emissions	Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring.	World Development Indicators (WORLD BANK, 2016)
CO_2 emission intensity	CO_2 emissions / Energy use	
Wellbeing Projections	Projected *pcIWI* = ((1 *r*) *pcIWI*)/Projected Pop	
IWI growth rates	Projected growth rate (*r*) derived from observed IWI trend in each region for 1990-2010 Compound annual growth rate for 2005-2010 (last 5 years) used to project 2011-2020 Compound annual growth rate for 2000-2010 (last 10 years) used to project 2021-2030 Compound annual growth rate for 1990-2010 (last 20 years) used to project 2031-2050	IWR 2014 (UNU-IHDP and UNEP 2014)
Projected population	Projected population for each RC5 region based on population growth in the no-policy baseline emission scenario in the IAM MESSAGE. Calibrated to 2010, start of projections.	LIMITS Scenario database (public) (Version 1.0.0) https://tntcat.iiasa.ac.at/LIMITSPUBLICDB
Energy Projections	Projected EC = Projected *pcEC* x Projected Pop Projected *pcEC*= EXP((LN(projected *pcIWI)* - a)/*b*)	
EC/IWI elasticities (*b*)	Estimated from log-log regressions on cross-section data for 2010 2011-2050: projections based on EC/IWI elasticities estimated from log-log regressions on cross-section data for 2010	
Decoupling rate	Upper bound rates calculated based on prorated highest decrease rates observed, to be applied in 10-year period (2011-2020). Lower bound rates calculated based on prorated highest increase rates observed, to be applied in 10-year period (2011-2020). Second highest rates used to avoid distortions from peaks in EIT and LAM.	
Projected population	Projected population for each RC5 region based on population growth in the IAM MESSAGE. Calibrated to 2010, start of projections.	LIMITS Scenario database (public) (Version 1.0.0) https://tntcat.iiasa.ac.at/LIMITSPUBLICDB
CO_2 Emissions Projections	Projected CO_2 emissions = Projected EC x Projected CO_2 emission intensities Two series of projected CO_2 emissions (based on lower bound and upper bound projected EC series) are calculated.	
Projected CO2 emission intensities LOWER and UPPER bounds	Projected CO_2 emission intensities = 2010 CO_2 emission intensity X Growth rates	
	2010 CO_2 intensity = 2010 CO_2 emissions / 2010	World Development

Data	Description	Sources
	Energy Use (for each region)	Indicators (WORLD BANK, 2016)
Growth rates	Four sets of annualized intensities growth rates for each region for the years 2011 through 2050 (2011-2020, 2021-2030, 2031-2040, 2041-2050) obtained from projected CO_2 emissions from fossil fuel combustion and industrial processes and primary energy consumption levels also from the no-policy baseline scenario of the IAM MESSAGE. Projected CO_2 intensity = Projected CO_2 emissions / Projected primary energy	LIMITS Scenario database (public) (Version 1.0.0) https://tntcat.iiasa.ac.at/LIMITSPUBLICDB
	Projected CO_2 emissions in 450 and 500ppm scenarios were obtained from IAM MESSAGE 450 and 500ppm scenarios, normalized to 2010.	

Appendix D – Table of region categorization.

Table D 1 - Region categorization.

Region	Countries in RC5 region*	Countries not included in this analysis	% world pop
OECD90	Australia, Austria, Belgium, Canada, Denmark, Fiji, Finland, France, French Polynesia, Germany, Greece, Guam, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Caledonia, New Zealand, Norway, Portugal, Samoa, Solomon Islands, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States of America, Vanuatu	French Polynesia, Guam, New Caledonia, Samoa, Solomon Islands, Switzerland, Vanuatu	14
Economies in transition (EIT)	Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Malta, Poland, Republic of Moldova, Romania, Russian Federation, Slovakia, Slovenia, Tajikistan, TFYR Macedonia, Turkmenistan, Ukraine, Uzbekistan, Yugoslavia	Azerbaijan, Belarus, Bosnia and Herzegovina, TFYR Macedonia, Uzbekistan, Yugoslavia	5
Asia (ASIA)	Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China, Hong Kong, Macao, Democratic People's Republic of Korea, East Timor, India, Indonesia, Lao PDR, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Singapore, Sri Lanka, Taiwan, Thailand, Viet Nam	Afghanistan, Bhutan, Brunei, Hong Kong, Macao, Korea DRP, East Timor, Lao PDR, Maldives, Papua New Guinea, Taiwan.	52
Middle East and Africa (MAF)	Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Cote d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Oman, Qatar, Reunion, Rwanda, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Syrian Arab Republic, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Yemen, Zambia, Zimbabwe	Angola, Burkina Faso, Burundi, Cape Verde, Central African Rep., Chad, Comoros, Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Guinea, Guinea-Bissau, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Namibia, Niger, Oman, Reunion, Rwanda, Sierra Leone, Somalia, Swaziland, Uganda, United Republic of Tanzania, Western Sahara	13

Region	Countries in RC5 region*	Countries not included in this analysis	% world pop
Latin America (LAM)	Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela	Bahamas, Barbados, Belize, Bolivia, Guadeloupe, Guyana, Martinique, Netherlands Antilles, Puerto Rico, Suriname, Trinidad and Tobago	8

* Region Categorization 5 as per IAMC AR5 Scenario Database, 2014.

Appendix E – Comparison with previous quantification efforts.

Based on the findings of this study, the four regions combined, representing 78 percent of global population (based on 2010 data), would require between 606-897 EJ per year and between 42.1 and 62.8 $GtCO_2$ per year by 2050 (Table 7), as well as 17,264 and 24,216 EJ of cumulative energy consumption and between 1,174 and 1,658 $GtCO_2$ of cumulative carbon emissions from 2011 to 2050 (Table 8) to achieve higher collective wellbeing. These refer to average primary energy consumption rates of approximately 78 to 116 GJ per capita by 2050.

PASTERNAK (2000) had estimated a range from 378 to 492 EJ of overall primary energy consumption needed to reach a global average primary energy consumption rate of approximately 108 GJ per capita.[122] UGURSAL (2014) had estimated about 419 EJ (or 10 billion toe) of additional energy consumption needed to reach a global average energy consumption rate of 105 GJ per capita. According to PASTERNAK (2000) this rate would be achieved in 2020 while, according to UGURSAL (2014), it would only be achieved by 2100. Notwithstanding the different timeframes, those estimates are at least 19 percent lower than those obtained in this study.

COSTA *et al.* (2011) applied historic correlations between HDI and per capita CO_2 emissions (from fossil fuels combustion) to estimate the carbon impact of reaching specific HDI thresholds. They estimated that between 850 and 1,100 $GtCO_2$ of cumulative CO_2 emissions between 2000 and 2050 would be needed for 85 percent of the total world population to achieve a minimum of 0.8 HDI by 2050. These estimates are considerably lower than those obtained in this study (1,174 and 1,658 $GtCO_2$ between 2011 and 2050), in particular considering the 9 years difference (projections start in 2000, as opposed to 2011 in the present study) and the small difference in the sample size (85 percent of total world population, contrasted with 78 percent in the present study).

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[122] This range refers to achieving a minimum of 4,000 kWh (or 14.4 GJ) per capita electricity consumption or an estimated (at 7.5 ratio) 108 GJ (or 2580 koe) per capita primary energy consumption.

LAMB AND RAO (2015) projected energy requirements and corresponding CO_2 emissions of reaching minimum thresholds in two dimensions of human wellbeing (social and economic) in three developing regions (Africa, Centrally Planned Asia, and South Asia) that together represent 67 percent of the world population (based on 2010 data). They employed a composite of six factors related to food, shelter, basic health and hygiene, and education, as well as the UN's life expectancy data as proxy measurements for the social dimension of human development. They used GDP per capita data as proxy for the economic dimension.

They estimated approximately 216 $GtCO_2eq$ of cumulative CO_2 emissions would be required to achieve minimum social wellbeing levels between 2011 and 2050 in Africa (up to 54 GJ/capita/year final energy consumption rate by 2050), 442 $GtCO_2eq$ in Centrally Planned Asia (up to 45 GJ/capita/year by 2050), and 345 $GtCO_2eq$ in South Asia (up to 44 GJ/capita/year by 2050). The three regions combined, representing 67 percent of the world population (based on 2010 data), would require a total of just over 1,000 $GtCO_2eq$ between 2011 and 2050.

Given the different regional aggregation, we can only compare the results from LAMB AND RAO (2015) for Asia with those obtained for the same region in this study. While they provide an estimate for Africa, in the present analysis Africa is included in MAF (Middle East and Africa), therefore the numbers are not directly comparable. See Appendix D for the region categorization used in this study.

According to their findings, Asia (Centrally Planned Asia and South Asia) would require 787 Gt $GtCO_2eq$ to achieve minimum social wellbeing levels, reaching a final energy consumption rate of up to about 45 GJ per capita by 2050. It is noteworthy, that LAMB AND RAO (2015) calculated emissions as a sum of all greenhouse gases for each region, only excluding GHG emissions associated with land-use change. In the present study, in contrast, only CO_2 emissions from fossil fuels and industry were taken in to account, which represent about 66 percent of all GHG emissions (excluding land use) in the LIMITS baseline run 2010 data. As such, their estimates for Asia would equate very roughly to about 519 $GtCO_2$.

However, it is also important to highlight that LAMB AND RAO (2015) used final energy consumption data while the present study used primary energy consumption data. Recalling that final energy refers to the conversion of primary energy sources into energy ready for transportation or transmission, and that in every conversion step some energy is always lost, final energy levels are always expected to be lower than the associated primary energy from which they derived. Final energy consumption per capita rates in Asia averaged roughly 70 percent of primary energy consumption rates over the 1990-2010 period (UNESCAP, 2017). As such, their estimates for Asia (519 $GtCO_2$) could equate roughly to a 64 GJ per capita primary energy consumption rate or to an emissions intensity rate of 8.1 $GtCO_2$/GJ.

Taken all these differences into account, the estimates for Asia in LAMB AND RAO (2015) are comparable to the range of 817 to 1,192 $GtCO_2$ of cumulative emissions from 2011 to 2050 associated with reaching primary energy consumption rates of 94 to 146 GJ per capita estimated in the present study, or emissions intensity rates of 8.2 to 8.7 $GtCO_2$/GJ. Therefore, their estimates for Asia are at least 36 percent lower than those obtained in this study.

Appendix F – Assessing the gaps in all regions (including OECD90).

Table F.1 presents the emissions shortfalls (gaps) between the 450-ppm carbon budget (i.e. associated with reasonably high chance of limiting the temperature increase to below 2 °C) and the estimated additional carbon emissions (*projected CO_2 emissions*) associated with future improvements in human wellbeing in all 5 regions (including OECD90) by 2050,[123] in all emissions scenarios considered.

Table F 1 - Emissions shortfall by 2050 per emissions scenario compared to the 450-ppm budget.

Region/ Scenario	**Immediate action-450 (budget)**	**Gap in No-action scenario**		**Gap in Delayed action-500 scenario**		**Gap in Action as of 2020-500 scenario**		**Gap in Action as of 2020-450 scenario**	
		at least	up to	at least	up to	at least	up to	at least	up to
ASIA	421	396	771	207	484	170	429	82	296
MAF	112	51	71	23	40	4	17	(9)	3
LAM	48	32	78	6	35	(8)	13	(11)	8
EIT	75	40	83	10	40	2	29	(8)	15
OECD90	256	155	268	53	134	46	161	8	75
Total all regions	**912**	**674**	**1,271**	**298**	**732**	**214**	**649**	**62**	**397**
Budget exceeded by (times)			**2.4**						**1.4**

Table F.2 presents all gaps between the 500-ppm carbon budget (i.e. associated with even chance of limiting the temperature increase to below 2 °C) and the estimated additional carbon emissions (*projected CO_2 emissions*) associated with future improvements in human wellbeing in all 5 regions (including OECD90) by 2050, in all emissions scenarios considered.

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[123] Future levels of wellbeing in OCDE90 were projected following the same criteria applied to the other regions until 2020 (section 4.3), thereafter it was assumed constant on a per capita basis (*pcIWI*).

Table F 2 - Emissions shortfall by 2050 per emissions scenario compared to the 500-ppm budget.

Region/ Scenario	**Immediate action-500 (budget)**	**Gap in No-action scenario**		**Gap in Delayed action-500 scenario**		**Gap in Action as of 2020-500 scenario**		**Gap in Action as of 2020-450 scenario**	
		at least	up to	at least	up to	at least	up to	at least	up to
ASIA	527	291	665	101	378	64	323	(24)	190
MAF	128	35	55	7	24	(12)	1	(25)	(13)
LAM	57	22	68	(4)	25	(17)	3	(21)	(2)
EIT	91	24	67	(6)	24	(13)	14	(23)	(0)
OECD90	308	104	216	1	82	(6)	109	(43)	24
Total 4 regions	**1,111**	**475**	**1,072**	**99**	**533**	**15**	**450**	**(136)**	**198**
Budget exceeded by (times)			**2.0**						**1.2**

Even if new climate policies and mitigation actions associated with reasonably high chances of meeting the 2 °C target, i.e. reaching GHG concentrations at roughly 450 ppm CO_2eq in 2100, were adopted in all four regions where improvements are still needed as well as in advanced countries (OECD90 region) in 2020, emissions associated with meeting the urgent energy needs while enabling the achievement of higher levels of collective wellbeing, could still exceed both estimated carbon budgets, the 450-ppm and the 500-ppm, by almost one and a half times (i.e. a gap of 397 $GtCO_2$) and by over one time (i.e. a gap of 198 $GtCO_2$), respectively, by mid-century.