ASSESSMENT OF THE ROLE OF NUCLEAR POWER ON ENERGY POLICIES AND CLIMATE CHANGE MITIGATION STRATEGIES OF DEVELOPING COUNTRIES

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ABSTRACT

ASSESSMENT OF THE ROLE OF NUCLEAR POWER ON ENERGY POLICIES AND CLIMATE CHANGE MITIGATION STRATEGIES OF DEVELOPING COUNTRIES

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Nuclear energy is considered as one of the climate change mitigation options in the energy supply sector by substituting electricity generated from base load fossil fueled power plants reducing GHG emissions. Internalizing the costs of CO_2 emissions provides an additional economic incentive for investment in nuclear energy both in developed and developing countries. While developed countries with stable energy demand are focused on the robustness and resilience of their energy systems, the priority of developing countries continues to be the strengthening of energy security in order to supply their increasing energy demand. Climate change is one of the major global commons problems of our society which requires long-term and ambitious strategies in order to transform the socioeconomic development to low-carbon energy pathways. The role of nuclear energy in transformation of the energy sector has been assessed by the climate change community on regional and global scales using various integrated assessment models. However there is a gap between the results of these studies and the quantitative commitments of countries for climate change mitigation in their NDCs submitted to the UNFCCC resulting in higher GHG emissions. In this study I show that the role of low-carbon energy supply options for climate change mitigation depends on global socioeconomic development pathways especially for developing countries already facing a transition in their economies and energy systems. The role of nuclear energy for supplying the electricity required for developing countries is dependent on global socio-economic pathways supporting investment in most stringent GHG emissions scenarios. Expert elicitation was used for MCA of energy supply system modeling results by integrating CO_2 emissions from power sector, flexibility of the electricity grid to supply peak load demand, change in welfare from carbon tax and transfer of revenues for subsidizing renewable energy, and the total discounted energy system costs. The results show that for the second commitment period of the Paris Agreement, the role of nuclear energy is for supporting the transition of the energy system to a low carbon future for both green transformation and regional rivalry scenarios.

Keywords: nuclear energy, climate change mitigation, energy transition, expert elicitation

ÖZ

GELİŞMEKTE OLAN ÜLKELERİN ENERJİ POLİTİKALARINDA VE İKLİM DEĞİŞİKLİĞİ AZALTIMI STRATEJİLERİNDE NÜKLEER ENERJİNİN ROLÜNÜN DEĞERLENDİRİLMESİ

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Nükleer enerji, sera gazı emisyonlarını azaltan baz yük fosil yakıtlı enerji santrallerinden üretilen elektriğin yerini alarak enerji tedarik sektöründeki iklim değişikliğini azaltma seçeneklerinden biri olarak kabul edilmektedir. CO_2 emisyon maliyetlerinin içselleştirilmesi, hem gelişmiş hem de gelişmekte olan ülkelerde nükleer enerjiye yatırım için ek bir ekonomik teşvik sağlar. İstikrarlı enerji talebi olan gelişmiş ülkeler enerji sistemlerinin sağlamlığına ve dayanıklılığına odaklanırken, gelişmekte olan ülkelerin önceliği artan enerji talebini karşılamak için enerji güvenliğinin güçlendirilmesi olmaya devam etmektedir. İklim değişikliği, sosyoekonomik kalkınmayı düşük karbonlu enerji yollarına dönüştürmek için uzun vadeli ve iddialı stratejiler gerektiren toplumumuzun en büyük küresel ortak sorunlarından biridir. Nükleer enerjinin enerji sektörünün dönüşümündeki rolü, iklim değişikliği topluluğu tarafından çeşitli birleşik değerlendirme modelleri kullanılarak bölgesel ve küresel ölçeklerde değerlendirilmiştir. Bununla birlikte, bu çalışmaların sonuçları ile ülkelerin Birleşmiş Milletler İklim Değişikliği Çerçeve Sözleşmesine sundukları ulusal taahhütlerde iklim değişikliğinin azaltılmasına yönelik nicel taahhütleri arasında daha yüksek sera gazı emisyonu ile sonuçlanan bir boşluk vardır. Bu çalışmada, iklim değişikliğinin azaltılması için düşük karbonlu enerji arz seçeneklerinin rolünün, özellikle ekonomilerinde ve enerji sistemlerinde bir geçişle karşı karşıya olan gelişmekte olan ülkeler için küresel sosyoekonomik kalkınma yollarına bağlı olduğunu gösterdim. Nükleer enerjinin gelişmekte olan ülkeler için gerekli elektriğin sağlanmasındaki rolü, en katı sera gazı emisyonları senaryolarına yatırımı destekleyen küresel sosyoekonomik yollara bağlıdır. Enerji sektöründen kaynaklanan CO_2 emisyonları, elektrik şebekesinin pik yük talebini karşılamak için esnekliği, karbon vergisinden refah değişikliği ve yenilenebilir enerjinin sübvanse edilmesi için gelir aktarımı ve toplam indirimli enerji sistemi maliyetleri entegre edilerek enerji tedarik sistemi modelleme sonuçlarının çoklu kriter analizi için uzman değerlendirmesi kullanılmıştır. Sonuçlar, Paris Anlaşması'nın ikinci taahhüt dönemi için nükleer enerjinin rolünün, hem yeşil dönüşüm hem de bölgesel rekabet senaryoları için enerji sisteminin düşük karbonlu bir geleceğe geçişini desteklemek olduğunu göstermektedir.

Anahtar Kelimeler: nükleer enerji, iklim değişikliği azaltımı, enerji dönüşümü, uzman değerlendirme

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TABLE OF CONTENTS

ABSTRACT v

ÖZ vii

ACKNOWLEDGMENTS ix

TABLE OF CONTENTS x

LIST OF TABLES xiii

LIST OF FIGURES xvi

LIST OF ABBREVIATIONS xxiii

CHAPTERS

1 INTRODUCTION 1

1.1 Research problem 3

1.2 Literature review 5

1.2.1 Climate mitigation strategies 7

1.2.2 Low carbon energy technologies 14

1.2.3 Energy supply system and environmental impacts 19

1.2.3.1 Input-output models 20

1.2.3.2 General equilibrium models 21

1.2.3.3 Partial equilibrium models 23

1.3 Turkish energy policy 26

1.4 Hypothesis and research questions 31

2 RESEARCH METHODOLOGY 35

2.1 Energy and climate scenarios 35

2.2 Energy supply system modeling 48

2.3 Socioeconomic and technological data 55

2.4 Robustness of electricity supply system 61

2.5 Earth system feed-backs 64

3 ANALYSIS OF RESULTS 67

3.1 Modeling results 67

3.1.1 Energy system costs 68

3.1.2 Electricity generation capacity 76

3.1.3 Electricity generation costs 85

3.1.4 Electricity grid flexibility 106

3.1.5 Atmospheric gas emissions 108

3.1.6 Nuclear fuel cycle costs 119

3.2 Expert elicitation on energy and climate policies 138

3.2.1 Literature review 139

3.2.2 Survey method 141

3.2.3 Climate change and nuclear power 147

3.2.4 Results and discussion 153

3.3 Sensitivity analysis 160

3.4 Validation of the hypothesis 164

4 DISCUSSION AND CONCLUSION 171

REFERENCES 179

APPENDICES

A MESSAGE CODE FOR ENERGY SYSTEM MODELING 203

B ENERGY LOAD REGIONS 229

C EXPERT ELICITATION SURVEY 233

D R CODE FOR MCA OF MODELING RESULTS 243

LIST OF TABLES

TABLES

Table 1.1 Social criteria and indicators 16

Table 1.2 Hypothesis tested in this study 34

Table 2.1 Models used for quantification of SSPs 36

Table 2.2 Final energy demand in SSP1 scenarios 43

Table 2.3 Final energy demand in SSP2 scenarios 44

Table 2.4 Final energy demand in SSP3 scenarios 44

Table 2.5 Definition of objective function variables 52

Table 2.6 Definition of energy demand function variables 52

Table 2.7 Definition of energy balance function variables 53

Table 2.8 Definition of energy capacity function variables 54

Table 2.9 Definition of river balance function variables 55

Table 2.10 Definition of hydro storage function variables 55

Table 2.11 Definition of resource function variables 55

Table 2.12 SO_2 emission factors from electricity generation in kton/MWyr . . . 56

Table 2.13 NO_x emission factors from electricity generation in kton/MWyr . . 56

Table 2.14 Transformation of the energy sector in annual rate of change (%/yr) . 57

Table 2.15 Technology variables for power plant technologies 58

Table 2.16 Technology variables for energy conversion technologies 58

Table 2.17 Oil product production shares of oil refineries 59

Table 2.18 Technology variables for nuclear fuel cycle 59

Table 2.19 Costs of primary energy sources in US$/kWyr 60

Table 2.20 Feasible potentials of primary renewable energy sources 60

Table 2.21 Domestic coal reserves in MWyr 61

Table 2.22 Flexibility parameters for the electricity grid 62

Table 2.23 Power change requirements for power plants (MW/hr) 63

Table 2.24 Global warming potentials for temporal scales of 20 and 100 years . 65

Table 3.1 Definition of end of horizon function variables 68

Table 3.2 Total energy system costs (billion US$) in SSP1 69

Table 3.3 Total energy system costs (billion US$) in SSP2 70

Table 3.4 Total energy system costs (billion US$) in SSP3 72

Table 3.5 Cumulative revenues from emission penalty costs (billion US$) . . . 72

Table 3.6 Definition of cumulative constraint variables 73

Table 3.7 Total payments used for FITs (billion US$) 75

Table 3.8 Shares of total FIT payments in revenues from emission penalties (%) 76

Table 3.9 CO_2 emissions from power sector (ton/MWyr) 109

Table 3.10 CO_2 emissions from final energy demand (ton/MWyr) 110

Table 3.11 Annual output for 1 GW NPP reactor unit 121

Table 3.12 Egoistic, altruistic and biospheric values 139

Table 3.13 Relations between dependent variables for egoistic values 143

Table 3.14 Relations between dependent variables for altruistic values 145

Table 3.15 Relations between dependent variables for biospheric values 146

Table 3.16 Relations between perceptions and environmental values 157

Table 4.1 Primary fossil energy demand (GW-year) in 2035 175

Table 4.2 Primary fossil energy demand (GW-year) in 2050 175

Table 4.3 Primary renewable energy demand (GW-year) in 2035 176

Table 4.4 Primary renewable energy demand (GW-year) in 2050 176

Table 4.5 Installed low carbon electricity capacity (GW) in 2035 176

Table 4.6 Installed low carbon electricity capacity (GW) in 2050 177

LIST OF FIGURES

FIGURES

Figure 1.1 Classitication of SRES scenarios 9

Figure 1.2 Classification of SSPs 11

Figure 1.3 Total final energy demand 27

Figure 1.4 Total primary energy supply 27

Figure 1.5 Sectoral GHG emissions 28

Figure 2.1 Mapping of SSP and RCP conditions for scenario development . 39

Figure 2.2 Input load curves for solar, wind and hydro power 40

Figure 2.3 Energy system modeling using MESSAGE 42

Figure 2.4 Final electricity demand normalized load curve 46

Figure 2.5 Final natural gas for residential heat demand normalized load curve 47

Figure 3.1 Energy system costs for RCPs in SSP1 compared to baseline . . 69

Figure 3.2 Energy system costs for RCPs in SSP2 compared to baseline . . 70

Figure 3.3 Energy system costs for RCPs in SSP3 compared to baseline . . 71

Figure 3.4 Energy system costs for RCPs with FITs in SSP1 compared to baseline 74

Figure 3.5 Energy system costs for RCPs with FITs in SSP2 compared to baseline 74

Figure 3.6 Energy system costs for RCPs with FITs in SSP3 compared to baseline 75

Figure 3.7 Electricity capacity expansion in SSP1 for Baseline 77

Figure 3.8 Electricity capacity difference in SSP1 for RCP4.5 78

Figure 3.9 Electricity capacity difference in SSP1 for RCP3.4 78

Figure 3.10 Electricity capacity difference in SSP1 for RCP2.6 79

Figure 3.11 Electricity capacity expansion in SSP2 for Baseline 80

Figure 3.12 Electricity capacity difference in SSP2 for RCP6.0 80

Figure 3.13 Electricity capacity difference in SSP2 for RCP4.5 81

Figure 3.14 Electricity capacity difference in SSP2 for RCP3.4 82

Figure 3.15 Electricity capacity difference in SSP2 for RCP2.6 82

Figure 3.16 Electricity capacity expansion in SSP3 for Baseline 83

Figure 3.17 Electricity capacity difference in SSP3 for RCP6.0 84

Figure 3.18 Electricity capacity difference in SSP3 for RCP4.5 84

Figure 3.19 Electricity capacity difference in SSP3 for RCP3.4 85

Figure 3.20 Marginal cost of electricity generation for SSP1 86

Figure 3.21 Electricity supply in SSP1 for Baseline [2035] 87

Figure 3.22 Electricity supply difference in SSP1 for RCP4.5 [2035] 88

Figure 3.23 Electricity supply difference in SSP1 for RCP3.4 [2035] 89

Figure 3.24 Electricity supply difference in SSP1 for RCP2.6 [2035] 89

Figure 3.25 Electricity supply in SSP1 for Baseline [2050] 90

Figure 3.26 Electricity supply difference in SSP1 for RCP4.5 [2050] 91

Figure 3.27 Electricity supply difference in SSP1 for RCP3.4 [2050] 91

Figure 3.28 Electricity supply difference in SSP1 for RCP2.6 [2050] 92

Figure 3.29 Marginal cost of electricity generation for SSP2 93

Figure 3.30 Electricity supply in SSP2 for Baseline [2035] 93

Figure 3.31 Electricity supply difference in SSP2 for RCP6.0 [2035] 94

Figure 3.32 Electricity supply difference in SSP2 for RCP4.5 [2035] 95

Figure 3.33 Electricity supply difference in SSP2 for RCP3.4 [2035] 95

Figure 3.34 Electricity supply in SSP2 for RCP2.6 [2035] 96

Figure 3.35 Electricity supply in SSP2 for Baseline [2050] 97

Figure 3.36 Electricity supply difference in SSP2 for RCP6.0 [2050] 97

Figure 3.37 Electricity supply difference in SSP2 for RCP4.5 [2050] 98

Figure 3.38 Electricity supply difference in SSP2 for RCP3.4 [2050] 99

Figure 3.39 Electricity supply in SSP2 for RCP2.6 [2050] 99

Figure 3.40 Marginal cost of electricity generation for SSP3 100

Figure 3.41 Electricity supply in SSP3 for Baseline [2035] 101

Figure 3.42 Electricity supply difference in SSP3 for RCP6.0 [2035] 101

Figure 3.43 Electricity supply difference in SSP3 for RCP4.5 [2035] 102

Figure 3.44 Electricity supply in SSP3 for RCP3.4 [2035] 103

Figure 3.45 Electricity supply in SSP3 for Baseline [2050] 103

Figure 3.46 Electricity supply in SSP3 for RCP6.0 [2050] 104

Figure 3.47 Electricity supply in SSP3 for RCP4.5 [2050] 105

Figure 3.48 Electricity supply in SSP3 for RCP3.4 [2050] 105
Figure 3.49 Annual electricity grid flexibility to supply peak load in SSP1 . . 106
Figure 3.50 Annual electricity grid flexibility to supply peak load in SSP2 . . 107
Figure 3.51 Annual electricity grid flexibility to supply peak load in SSP3 . . 108
Figure 3.52 CO_2 emissions from energy sector in SSP1 111
Figure 3.53 Kaya identity decomposition of CO_2 emissions in SSP1 111
Figure 3.54 CO_2 emissions from energy sector in SSP2 112
Figure 3.55 Kaya identity decomposition of CO_2 emissions in SSP2 113
Figure 3.56 CO_2 emissions from energy sector in SSP3 113
Figure 3.57 Kaya identity decomposition of CO_2 emissions in SSP3 114
Figure 3.58 SO_2 emissions from power generation for RCPs in SSP1 115
Figure 3.59 NO_x emissions from power generation for RCPs in SSP1 116
Figure 3.60 SO_2 emissions from power generation for RCPs in SSP2 116
Figure 3.61 NO_x emissions from power generation for RCPs in SSP2 117
Figure 3.62 SO_2 emissions from power generation for RCPs in SSP3 118
Figure 3.63 NO_x emissions from power generation for RCPs in SSP3 119
Figure 3.64 Complete nuclear fuel life-cycle 120
Figure 3.65 Annual nuclear fuel cycle cost in SSP1 for Baseline 122
Figure 3.66 Spent nuclear fuel storage in SSP1 for Baseline 122
Figure 3.67 Annual nuclear fuel cycle cost difference in SSP1 for RCP4.5 . 123
Figure 3.68 Spent nuclear fuel storage difference in SSP1 for RCP4.5 124
Figure 3.69 Annual nuclear fuel cycle cost difference in SSP1 for RCP3.4 . 124

Figure 3.70 Spent nuclear fuel storage difference in SSP1 for RCP3.4 125

Figure 3.71 Annual nuclear fuel cycle cost in SSP2 for Baseline 126

Figure 3.72 Spent nuclear fuel storage storage in SSP2 126

Figure 3.73 Annual nuclear fuel cycle cost difference in SSP2 for RCP6.0 . 127

Figure 3.74 Spent nuclear fuel storage difference in SSP2 for RCP6.0 128

Figure 3.75 Annual nuclear fuel cycle cost difference in SSP2 for RCP4.5 . 128

Figure 3.76 Spent nuclear fuel storage difference in SSP2 for RCP4.5 129

Figure 3.77 Annual nuclear fuel cycle cost difference in SSP2 for RCP3.4 . 130

Figure 3.78 Spent nuclear fuel storage difference in SSP2 for RCP3.4 130

Figure 3.79 Annual nuclear fuel cycle cost difference in SSP2 for RCP2.6 . 131

Figure 3.80 Spent nuclear fuel storage difference in SSP2 for RCP2.6 132

Figure 3.81 Annual nuclear fuel cycle cost in SSP3 for Baseline 133

Figure 3.82 Spent nuclear fuel storage in SSP3 for Baseline 133

Figure 3.83 Annual nuclear fuel cycle cost difference in SSP3 for RCP6.0 . 134

Figure 3.84 Spent nuclear fuel storage difference in SSP3 for RCP6.0 135

Figure 3.85 Annual nuclear fuel cycle cost difference in SSP3 for RCP4.5 . 135

Figure 3.86 Spent nuclear fuel storage difference in SSP3 for RCP4.5 136

Figure 3.87 Annual nuclear fuel cycle cost difference in SSP3 for RCP3.4 . 137

Figure 3.88 Spent nuclear fuel storage difference in SSP3 for RCP3.4 137

Figure 3.89 Relations used in expert elicitation survey 142

Figure 3.90 Importance of egoistic values 143

Figure 3.91 Importance of altruistic values 144

Figure 3.92 Importance of biospheric values 145

Figure 3.93 Cluster model for value orientations 146

Figure 3.94 Gender distribution of sample population 147

Figure 3.95 Age distribution of sample population 148

Figure 3.96 Profession distribution of sample population 149

Figure 3.97 Degree distribution of sample population 149

Figure 3.98 Climate change perception for gender and age 150

Figure 3.99 Climate change perception for profession and degree 151

Figure 3.100 Climate change-energy trade-off and gender 152

Figure 3.101 Climate change-energy trade-off and profession 152

Figure 3.102 Nuclear energy perception for gender 153

Figure 3.103 Nuclear energy perception for age 154

Figure 3.104 Nuclear energy perception for profession 154

Figure 3.105 Nuclear energy perception for degree 155

Figure 3.106 Importance of low carbon energy sources 157

Figure 3.107 Importance of fossil energy sources 158

Figure 3.108 Safety perception of power generation technologies 159

Figure 3.109 Safety perception of energy conversion technologies 160

Figure 3.110 Primary fossil fuel costs for Baseline in SSP1 162

Figure 3.111 Low carbon fuel costs for Baseline in SSP1 162

Figure 3.112 Primary fossil fuel costs for RCP2.6 in SSP1 163

Figure 3.113 Low carbon fuel costs for RCP2.6 in SSP1 164

Figure 3.114 Primary fossil fuel costs for Baseline in SSP2 165

Figure 3.115 Low carbon fuel costs for Baseline in SSP2 165

Figure 3.116 Primary fossil fuel costs for RCP2.6 in SSP2 166

Figure 3.117 Low carbon fuel costs for RCP2.6 in SSP2 166

Figure 3.118 Primary fossil fuel costs for Baseline in SSP3 167

Figure 3.119 Low carbon fuel costs for Baseline in SSP3 167

Figure 3.120 Primary fossil fuel costs for RCP3.4 in SSP3 168

Figure 3.121 Low carbon fuels for RCP3.4 in SSP3 168

Figure 3.122 Energy and carbon intensity change for SSPs (%/yr) 170

Figure 4.1 MCA of SSP1 scenarios 172

Figure 4.2 MCA of SSP2 scenarios 173

Figure 4.3 MCA of SSP3 scenarios 174

LIST OF ABBREVIATIONS

ABBREVIATIONS

AIM	Asia-Pacific Integrated Assessment
AIMES	Analysis, Integration and Modeling of the Earth System
AR5	Fifth Assessment Report
CBDR	Common but Differentiated Responsibilities
CCGT	Combined Cycle Gas Turbine Power Plant
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CGE	Computable General Equilibrium
CHP	Combined Heat and Electricity Production Power Plant
COP	Conference of Parties
CRP	Coordinated Research Project
EKC	Environmental Kuznets Curve
EU	European Union
FEEM	Fondazione Eni Enrico Mattei
FGD	Flue Gas Desulphurisation
FIT	Feed-in Tariff
GAMS	General Algebraic Modeling System
GCAM	Global Change Assessment Model
GCM	General Circulation Model
GDP	Gross Domestic Product
GEA	Global Energy Assessment
GHG	Greenhouse Gas
GLPK	GNU Linear Programming Kit

GTAP	Global Trade Analysis Project
HM	Heavy Metal
I/O	Input-Output
IAEA	International Atomic Energy Agency
IAM	Integrated Assessment Modeling
IAV	Impacts, Adaptation and Vulnerability
IEA	International Energy Agency
IGBP	International Geosphere-Biosphere Programme
IIASA	International Institute for Applied Systems Analysis
IMAGE	Integrated Model to Assess the Global Environment
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Electricity
LULUCF	Land Use, Land Use Change and Forestry
MAGICC	Model for the Assessment of Greenhouse Gas Induced Climate Change
MCA	Multi-criteria Analysis
MER	Market Exchange Rate
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
NDC	Nationally Determined Contribution
NEA	Nuclear Energy Agency
NEEDS	New Energy Externalities Development for Sustainability
NEI	Nuclear Energy Institute
NGO	Non-governmental Organization
NIES	National Institute for Environmental Studies
NPP	Nuclear Power Plant

NSG	Nuclear Suppliers Group
OECD	Organization for Economic Cooperation and Development
PBL	Netherlands Environmental Assessment Agency
PIK	Potsdam Institute for Climate Impact Research
PNNL	Pacific Northwest National Laboratory
POLES	Prospective Outlook on Long Term Energy Systems
PPP	Purchasing Power Parity
PSA	Probabilistic Safety Assessment
PV	Photo-Voltaic
RC	Respective Capacities
RCP	Reference Concentration Pathways
RegCM3	Third Generation Regional Climate Model
REMIND	Regionalized Model of Investments and Development
ROR	Run-off-river
SCR	Selective Catalytic Reduction
SDG	Sustainable Development Goal
SEM	Structural Equation Modeling
SPV	Special Purpose Vehicle
SRES	Special Report on Emissions Scenarios
SSP	Shared Socioeconomic Pathway
SWU	Seperative Work Unit
TAR	Third Assessment Report
UNFCCC	United Nations Framework Convention on Climate Change
UAE	United Arab Emirates
USA	United States of America
WITCH	World Induced Technical Change Hybrid Model

CHAPTER 1

INTRODUCTION

Investments for new NPPs are considered in many developing countries as major capital investment projects and one of the strategies for national economic development and energy supply security. Nuclear energy was utilized for electricity generation first by nuclear weapon states following the end of the second world war which was spread out to other countries through cooperation for peaceful use of nuclear technologies [165]. During the oil crisis of the 1970s many countries experiencing energy security problems also shifted to nuclear energy including industrialized countries such as France and Japan and also developing countries such as India and South Korea which eventually became nuclear technology vendor countries [173]. This period is also characterized with liberation of the economies and energy sectors resulting in slowing down of NPP investments through public financing in many countries including United Kingdom [91] and Turkey [109].

The usage of nuclear energy requires strict regulations during construction and operation of NPPs due to government responsibility for protection of the public against possible accidents resulting in significant amount of radioisotope release to the environment. Therefore nuclear energy has specific economic, environmental and social impacts which are generally assessed using multi-disciplinary framework for sustainable development [105]. After signature of the Paris Agreement, signatories submitted their NDCs to the UNFCCC where nuclear energy is also considered as one of the national policies for many countries to reduce GHG emissions from the energy sector.

Nuclear energy investments are considered as one of the strategies for supporting national and local economic and industrial development. However the impact of nuclear energy on the development of the energy system, environmental protection and socio-economic development needs further assessment in order to provide the scientific basis on the role of nuclear energy for sustainable development. Many international organizations such as the IAEA, OECD and World Bank supports infrastructure development by providing project funding under international or regional cooperation mechanisms to help developing nations address these issues.

Many countries in the world lack the incentive or the institutional capacity to develop the scientific basis in order to assess energy policies for GHG emission reductions [40]. As a result there are various academic studies from these countries focusing on the assessment of energy policies and their roles for issues such as energy security and climate mitigation. The main beneficiaries of these studies are energy policy makers and electricity market players including utilities, regulators, governmental authorities and final energy consumers. Low income countries are particularly in focus of these studies as climate change affects them the most requiring additional mechanisms for climate adaptation [67]. McCollum et al. study use MESSAGE for assessment of the synergy between energy sustainability objectives such as energy security improvement, climate change mitigation and reduction of air pollution [115]. The study concludes that there are positive benefits on energy security and human health in the near term with positive impact on climate in the medium to long term from implementation of cost effective climate-pollution-security policies.

The main stakeholders of new build NPP projects are utility investors and owners, safety authorities and market regulators together with national and regional government authorities responsible for economic development, energy security and environmental protection. Regional authorities may have positive or negative support to nuclear energy depending on their trade-offs between economic, environmental and social impacts depending on national preferences. NGOs may also have positive or negative support depending on the general mandate of their organizations and general public opinion concerning nuclear energy. The wide range of stakeholders create potential for expert elicitation with disciplinary backgrounds ranging from engineers to social scientists and legal experts [30].

The role of nuclear energy for climate change mitigation policies is not only through the reduction of GHG emissions but also from the development pathways of the energy market effecting investments for other low carbon technologies. The effectiveness of the energy market also relies on national policies concerning energy security, air pollution, energy demand side management and transformation of the energy sector [156]. The main assumptions for energy system modeling are the costs for construction and operation of power plants, energy flows including upstream and downstream activities and GHG emissions from production activities. Simulations of energy markets provide additional opportunity to represent energy policies and pricing mechanisms which does not rely solely on optimization of internalized costs [177].

The transition of the energy system to a diversified and low carbon future also requires policies for downstream activities especially in energy services. The electricity market liberalization continues with un-bundling of energy services despite the high rate of loss and theft in many developing countries which damages the profitability of utilities. The increasing marginal prices for residential electricity and natural gas for heating favors investment in energy efficient devices and energy conservation. The regulatory policies for energy efficiency require investments especially for heat insulation of buildings and refurbishment of facilities to consume less energy which are defined as low hanging fruits of implementing climate policies [36].

1.1 Research problem

The general research question explored in this study is "How will the energy supply systems of developing countries evolve after COP21 of the UNFCCC and especially during the second and third commitment period of the Paris Agreement?". Although the Paris Agreement was adopted in 5 October 2016, there are still many questions on issues such as the CBDRs and RCs of countries resulting in spatial and temporal differences in implementation of NDCs [71]. There are also countries such as the USA with different views on climate change between states and the federal government [125] and Turkey which has signed but not yet ratified the Paris Agreement. So under this circumstance the general question is supported by "Why does international cooperation efforts lag behind in implementation of NDCs?". This study aims to explore the following questions for developing countries.

- What is the role of nuclear power in energy supply system development for climate mitigation strategies?
- How does the global socio-economic pathways effect the transformation of the national energy sectors towards low carbon pathway?
- Which policies are most preferable for reduction of cumulative GHG emission from energy supply system?
- Which personal motivations and preferences are associated with favoring and supporting transition towards low carbon pathway?

The research required for exploring these questions is inter-disciplinary with natural sciences and engineering used for analytical modeling of the energy supply system and social sciences used for elaboration of socioeconomic development pathways and preferences of stakeholders for low carbon transformation. Socio-economic development scenarios based on SSPs and climate scenarios based on RCPs are developed by IPCC through international collaboration and many research organizations conduct modeling studies for quantification of these scenarios for the subjects listed below [48].

- Energy sectoral demand
- Fossil energy resource costs
- Energy supply costs
- Land use and productivity costs
- Food consumption and environmental impact

Energy supply system modeling studies are based on national and international databases for calculation of inputs and assumptions on development pathways as the future is largely uncertain and in most cases non-linear as there are increasing opportunities for shifting to green growth paradigm [183]. This study aims to integrate the social and technical characteristics using linear optimization of energy supply system and social preferences using expert elicitation on future development of energy system and climate policies. The contribution of this approach is to integrate social sciences to energy policy assessment powered by individual preferences and community initiatives instead of solely being based on energy simulation and cost optimization modeling studies [167].

Mathematical modeling of energy system has strengths for explicit representation of energy technologies and long term climate action pathways but also weaknesses to represent behaviors and interviewer bias in analyzing information in values and behaviors of respondents [166]. Energy models used by universities and research institutes provide a foresight on how the future energy system would evolve and what would be their general environmental impacts. However depending on the research question and the specific objective of research, specific models provide advantages to the researcher in order to explore in depth certain aspects such as climate mitigation, energy security or air pollution.

The results from the economic, energy system and environmental modeling studies produces a set of Pareto-optimal solutions representing future pathways for sustainable energy system development and for further elaboration with MCA [139]. The national preferences are defined by specifying the values desired to be achieved and to be avoided for the indicators used in the modeling studies. The range of the values defined for the indicators are assessed using multi-criteria analysis method to define the Pareto-optimal solution for energy system development of Turkey representing the national preferences. The results of the project are expected to support the scientific basis for the assessment of the role of nuclear energy for climate mitigation strategy of Turkey.

1.2 Literature review

The literature review focuses on studies concerning climate change mitigation strategies and energy modeling studies which assess these studies for low carbon transformation of the energy system. This study was supported by the CRP of the IAEA with title "Assessments of the Potential Role of Nuclear Energy in National Climate Change Mitigation Strategies” where representatives from different countries presented their energy and climate strategies [74]. These presentations are summarized for the countries focusing on the references provided by their representatives.

Energy modeling tools are based on either optimization of internalized costs or simulation of supply-demand energy balance based on consumer preferences [55]. Energy models are also included to IAM frameworks including sectoral linkages, feedback loops, learning processes and individual behavior. Although the study focuses on the role of nuclear power for climate change mitigation, special emphasis is given to renewable energy sources in the power sector with support by FITs collected from atmospheric emission penalty costs.

The study contributes to the references studies listed below selected as baseline by integrating social sciences using expert elicitation survey for preferences of energy experts on issues related to climate change and energy policy [19]. These studies include thesis approved by METU and academic article based on the extension of these thesis.

- Ari (2010) thesis on CO_2 emissions from Turkish electricity sector for energy scenarios using IPCC methodology [4]
- Yildiz (2015) thesis on multi-criteria assessment of Turkish energy sector using non-linear programming in GAMS [192]
- Kat (2018) article on planned renewable and nuclear subsidy schemes using CGE model and GTAP-Power database [94]
- Onenli (2019) thesis on energy scenario development using linear programming in GAMS [135]

Global climate models are used inside IAM frameworks with energy sector represented by general or partial equilibrium energy system models [88]. The studies focus on the feasibility of achieving climate targets on global scale assessing issues such as inter-regional cooperation and temporal scale of emission reductions [171]. General equilibrium models are able to capture the interchanges between energy and other commodity markets however under a lack of technological representation [14]. Partial equilibrium models focus on certain sectors with technological detail together with assumptions on other commodity sectors and interchanges between them. The integration of these two methods is used as a solution to integrate the advantages of these approaches however creating additional modeling biases.

The studies for global energy system modeling used as baseline in this study are listed below. These studies include review of energy modeling tools for low carbon transformation with emphasis on assessing the results using MCA by integrating preferences of various stakeholders.

- Visschers et al. (2011) article on public acceptance of nuclear energy for Swiss public using SEM statistical method [187]
- Nakata et al. (2011) article on review of energy modeling methods for transformation to a low carbon society [126]
- Lehtveer et al. (2015) article on global assessment of nuclear power using MESSAGE and multi-criteria decision analysis [105]
- Chen et al. (2016) article on global economic modeling for climate change assessment using CGE model and GAMS mixed-complementary problem solver [32]

1.2.1 Climate mitigation strategies

As climate change is a global commons problem, addressing actions through national low carbon transformation has higher potential for achievement of international cooperation through dispersion of technologies to developing countries with increasing emissions [86]. However the differentiation of the socio-economic development and historical responsibilities of countries creates challenges for global action. Therefore in order to support international efforts governments established IPCC for scientific collaboration and signed the UNFCCC for adhering to global climate action. The key milestones from the beginning of these efforts are summarized in the list below [174].

- IPCC formed in 1988

- UNFCCC signed by governments in 1992 at Earth Summit and entered into force in 1995
  - Stabilize the GHG concentration in the atmosphere to prevent human induced climate change
  - Developed countries agree to return to 1990 emission levels
- IPCC's second report in 1995 includes statement that humans are responsible for climate change
- Kyoto Protocol adopted in 1997 and entered into force in 2005
  - Legally binding agreement for climate protection
  - Only developed countries (Annex B) required for emission reductions
  - Lack of global climate goal
  - Entry into force in 2005
  - Not ratified by all Annex B countries
  - Failed to provide a comprehensive and efficient solution
- Bali COP13 in 2007, Copenhagen COP15 in 2009, Cancun COP16 in 2010 agreed with 2 °C maximum temperature increase
- IPCC release of SRES in 2000
  - Development of new scenarios for IPCC TAR
  - Consequences of climate change in the absence of mitigation and adaptation measures
  - Mitigation and adaptation possibilities and costs in different regions and economic sectors
- Durban COP17 in 2011 established Ad Hoc Working Group on the Durban Platform for Enhanced Action
- Warsaw COP19 in 2013 provided INDCs
- IPCC release of AR5 in 2014
  - Comprehensive assessment of sea level rise over the past few decades

- Estimation of cumulative CO_2 emission since pre-industrial times and the remaining carbon budget for future emissions

- Paris Agreement adopted in 2015 and entered into force in 2016
  - All countries have legally binding obligations to submit their NDCs
  - Climate policies are determined by national governments

Climate scenarios in the IPCC SRES (Figure 1.1) represented development prioritizing economic or environmental preferences and global cooperation or regional rivalry [162]. The report was significantly different than previous risk assessment studies as both the risks and uncertainties are significantly higher resulting in research for plausible future stories which are different from historic trends. There were also many criticisms on the main assumptions of the study such as the convergence of GDPs between OECD and non-OECD countries and usage of MER instead of PPP resulting in challenges with communication of the results with the public. Although studies on public perception of climate change focus mostly on developed countries, recognition of human impact on climate change is increasing in developing nations whereas there is growing scepticism in some developed countries [29].

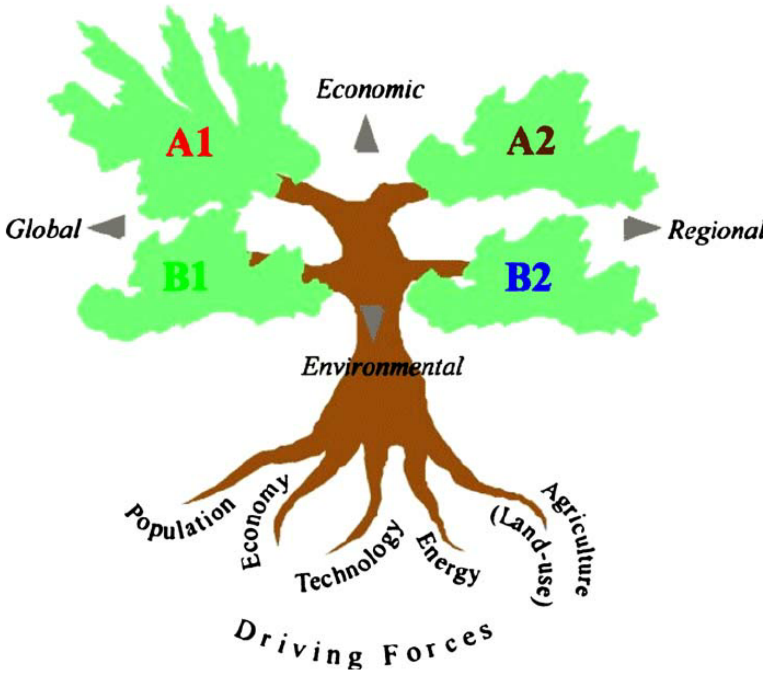

Figure 1.1: Classitication of SRES scenarios

Climate change is one of the major global problems with long term effects and includes many uncertainties concerning the costs of GHG reduction and adaptation [70]. These uncertainties are represented with additional calculation modules in IAMs favoring lower discount rates. The long residence time of carbon in the atmosphere causes intergenerational relation and the uncertainties includes intragenerational debate on who is more responsible and what is the extent of this responsibility [97]. Climate change can be considered as a public good which can be included in utility maximization models together with private goods represented by production factors [189]. However the temporal scale of climate action efforts makes achieving climate targets challenging as early movers benefit from higher welfare while the remaining non-action countries threaten the achievement of global collaborative action.

There are also risks of late accession as the early action countries would transform their infrastructures to a low carbon system and market carbon with prices which can not be adopted by late comers due to carbon lock-in of their energy systems [12]. Investment for low carbon transition of the energy sector could also exceed the requirements for other SDGs such as energy access, food security, air pollution and clean water and sanitation. The carbon budget consumed by cumulative emissions with higher emissions in the initial years could be offset with zero or negative emissions after year 2030 as the first commitment period of the Paris Agreement. However this requires further investments for refurbishment of installed power plants with CCS or their premature retirement resulting in higher total energy system costs.

The historical responsibilities of countries differ both spatially and temporally where developed countries have reached saturation in energy demand and developing countries continue to rely on increasing energy demand for their development [176]. The main objective of global climate action is to achieve unity in socio-economic development until the end of this century and leaving nobody behind in order to guarantee equity between regions and countries. However the climate action of countries with the extent based on CBDR and RC capacities no longer guarantees the achievement of climate target as the depletion of global carbon budget will require additional mitigation strategies adopting negative emissions [181]. The CBDR and RC of countries are important for future stocktaking of major GHG emissions countries and their recent trends in production [71]. They also define the extent of the climate ambition of countries as moral responsibilities should be weighed with respective capacities.

During the process to the IPCC AR5, climate change adaptation was also considered as important mechanism as human induced climate change is inevitable and efforts for climate change mitigation and adaptation should be optimized globally [84]. Therefore development studies for SSPs focus on the challenges for climate change mitigation and adaptation depending on the narratives used for global development [153]. These pathways include stories for demographics such as population growth and urbanization, technological improvements linked with resource availability and prices, and feed-backs with ecological services such as food and water as classified in Figure 1.2 [10]. These quantified assumptions are used as inputs in IAMs in order to assess future primary energy supply to meet the energy demand from population growth and production.

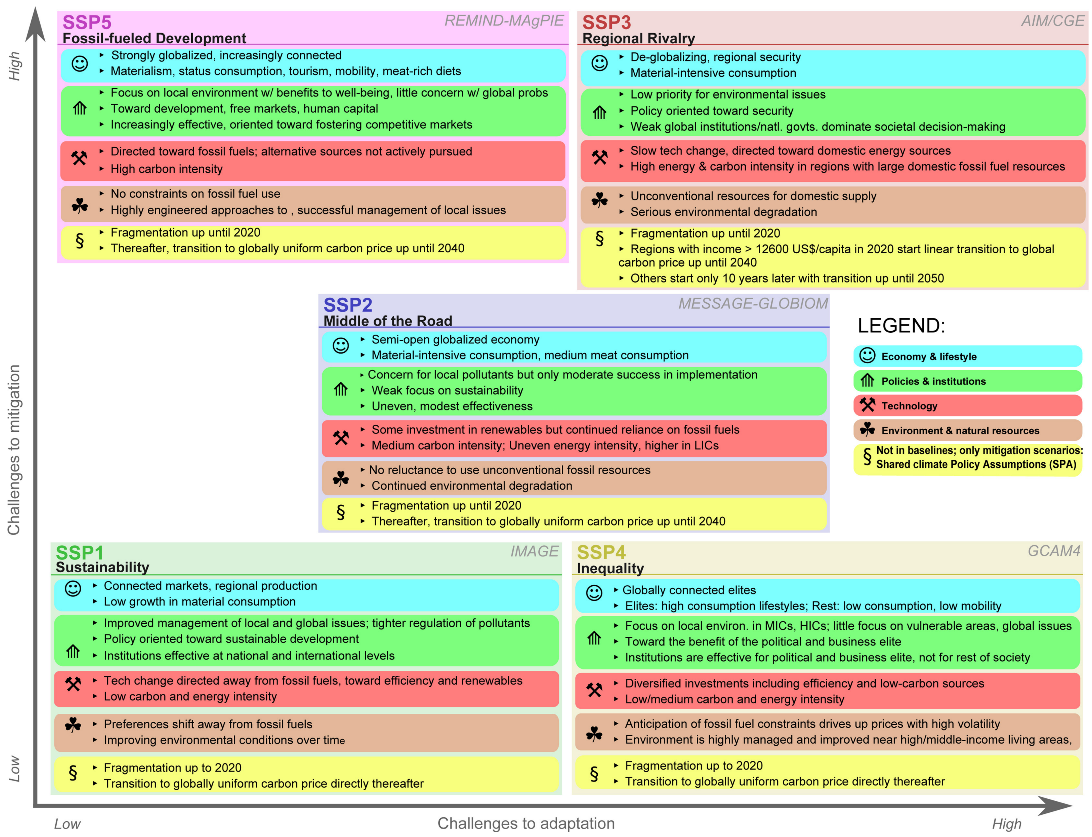

Figure 1.2: Classification of SSPs

The climate action required to achieve the climate target of the Paris Agreement requires ambitions on national level which are dependent on assumptions for socioeconomic development forecasts [69]. Despite the global coverage of NDCs, the spatial and temporal difference in the effects of climate change creates impacts on countries with different levels. Although financing mechanisms listed below such as the CDM of the Kyoto Protocol provide incentives for low carbon transition, the cumulative impact of these transnational initiatives are too low to achieve the climate targets [119].

- Economic instruments such as investment subsidies
- Taxes and tax exemptions
- Regulatory instruments such as mandated emissions targets, performance standards and emission controls
- Policy instruments such as voluntary agreements, consultation and strategic planning

The usage of additional flexibility mechanisms of the Kyoto Protocol such as voluntary carbon trading provides an opportunity for countries facing higher costs to finance mitigation efforts of countries with lower marginal costs of abatement resulting in reduced cumulative GHG emissions [5]. There are also large uncertainties associated with ambiguous and conditional targets of developing countries leading to uncertainties in future GHG emissions [157]. However the uncertainties in climate change impacts and the different types of NDC contents listed below creates difficulties in establishing these flexibility mechanisms.

- Variations in socio-economic baseline
- Variations in historical emission estimates
- Availability of financing mechanisms for NDCs and target range specification
- Different energy accounting mechanisms for renewable energy
- Attribution of traditional biomass usage

Eventually the application of IAMs together with global climate models generate forecasts for radiative forcing until the end of the 21st century by integrating biogeochemical reactions such as the Carbon and Nitrogen cycles in the earth system.

The feedback from carbon cycle, aerosol forcing and ocean uptake characteristics have been integrated to climate models including climate sensitivity [116]. One of the examples of a simple climate model is MAGICC-6 which is based on results from global IAM studies using simplified representations of GCMs for assessment of radiative forcing and temperature change resulting from climate change. The most important variables used in this model are climate feedbacks to carbon cycle and climate sensitivity to changes in radiative forcing due to GHG emissions. Marcucci and Turton study compare results from different IAMs to analyze the impact of prompt and delayed participation to climate change mitigation on energy technology deployment and development [112]. The results show that the first movers could face the risk of fossil fuel leakage and lower deployment of new technologies whereas they could also have advantages from intellectual property rights, exports and political leverage.

Krey reviews 162 recent medium to long term scenarios from 15 IAMs to assess the role of renewable energy in climate change mitigation [100]. The study presents a high uncertainty on the linkage between renewable energy and climate change mitigation due to uncertainties on the evolution of renewable energy technologies, competitiveness of other climate change mitigation options and driving forces for energy demand. Pindyck further reviews IAMs for estimating the social cost of GHG emissions and evaluation of alternative GHG emission abatement policies emphasizes the requirement for integration of feedback effects from climate change represented by major assumptions in the models [144]. The social cost of carbon ranges from 10 to 1000 US$/t$CO_2$ between countries with countries with population and GDP growth rate on the higher range [154]. The social cost of carbon depends on socio-economic assumptions, earth system feedback, environmental damages which are region specific and discount rate as the impacts of climate change are long term and global with uncertainties.

The results of global climate models has been further assessed by different spatial and temporal pathways of energy system development. The scenarios listed in SRES were assessed using top-down approach with lesser technological representation where the substitution of fossil fuels with low carbon energy sources was considered as an additional bottom-up contribution. Miller et al. [120] focused on the results of delay to climate change mitigation and critiques political motives for the exclusion of nuclear energy from climate change mitigation as substitution of additional fossil fuels mitigates the radiative forcing increase. The A1FI fossil intensive and B2 scenario including nuclear energy and liquid fuels with hydrogen were compared using MAGICC. The study shows that climate change could be slowed down in B2 scenario although high new nuclear build capacity is required until 2050.

There are also studies using GCMs on the regional level to forecast the impacts on climate change for climate vulnerability assessment. GCMs have a low resolution of the earth which could be down-scaled in order to capture the vulnerabilities and impacts or they can be used as regional circulation models. Önol et al. [136] study using regional climate model RegCM3 to assess climate change scenario impacts on Turkey concludes reduced run-off in Fırat and Dicle basins in the eastern part in winter and increasing surface temperatures in the western part in summer. Similar results are generated by Yılmaz et al. [193] showing decrease of water potential in Konya, Fırat and Dicle basins. There are also significant shifts in snow melt times with either no change or decrease in annual run-off in Eastern Anatolian river basins [195].

Schimel et al. [163] review the IGBP AIMES project describing challenges from inter-disciplinary approach to climate modeling with including the human dimension as the major forcing to climate change. In the beginning of the project, stakeholders had differing time scales and observational resources which was overcome by their learning to be very clear about assumptions and presumptions associated with their perspectives. The objective was to achieve deeper and more quantitative scientific understanding of interactions and feedback in the earth system under process and parameterization studies, regional-global integration, applied earth system science and earth system dynamics themes. The project resulted with a further requirement to integrate very slow and long term human dynamics which are not observable at IAM horizons.

1.2.2 Low carbon energy technologies

Rapid expansion of renewable energy technologies for low carbon transformation has interaction with the availability and prices of fossil fuel resources which are used as inputs for IAM of SSPs [11]. Lower reliance of nations on these fossil fuels has potential to improve their energy security by increasing the resilience of their energy systems in the first half of 21st century before zero or negative emissions are required for achieving the most stringent climate targets [33]. The main elements of SSPs focusing on the energy sector are summarized below [10].

- SSP1: Taking the green road
  - Decoupling of economic growth and energy consumption
  - Change of lifestyle towards low energy demand
  - Rapid technological developments and international cooperation
- SSP2: Middle of the road
  - Energy intensity improvement continue with historical rates
  - Slower convergence of growth in developing countries
  - Slower shift in primary energy mix
- SSP3: Regional rivalry
  - Fast population and slow economic growth in developing countries
  - Slow technological development and little environmental awareness
  - Concerns for energy security favors domestic coal usage and limit energy import

Besides renewable energy technologies as low carbon energy sources, the role of nuclear energy for reduction of GHG emissions is assessed by many researchers. Apergis et al. focus on causality between nuclear and renewable energy consumption and economic growth for a group of developed and developing countries from 1984 to 2007 using panel error correction method [3]. The study concludes that nuclear energy has a long run causality relationship with GHG emissions whereas renewable energy does not only reduce GHG emissions but also contributes to economic growth and energy security.

The relation between climate mitigation strategies and energy security nexus are assessed by Jewell et al. using 43 scenarios generated by MESSAGE as part of GEA study [89]. The results show that low carbon scenarios are generally associated with lower energy trade and higher diversity of energy options especially in the transport sector and recommending that national energy security assessments should take into consideration of the global context as well.

The usage of social indicators for energy system assessment is becoming more important as capturing the results of human actions due to behavioral and social factors remains challenging for IAM studies [142]. Carrera and Mack review the social indicator selection process listed in Table 1.1 under the NEEDS project using surveys for experts from countries including France, Germany, Italy and Switzerland [30]. The study concludes that NPPs, hydro-power, pulverized coal steam plant and gas turbine combined cycle will be the most predominant energy conversion technologies for the EU countries.

Table 1.1: Social criteria and indicators

Criteria	Background	Indicators
Security	High dependency of EU countries on external energy sources	Technological flexibility to incorporate innovations and availability of a complete infrastructure for waste disposal
Stability	The ability of society to cope with conflicts from deficiencies in energy supply	Potential for conflict induced by energy system and participative decision-making in site selection of energy systems
Risks	Recognition of social and individual risks by the society	Health consequences of normal operation, familiarity with risks, perceived catastrophic potential
Quality	Impacts of energy systems on human life and environment	Functional and aesthetic impacts on landscape

The sustainability studies of energy systems is also becoming more important for investors and utilities as unexpected extreme events could result in unrepairable damages to corporate images. Roth et al. [159] summarize the case study conducted for Axpo Holding AG on the sustainability of Swiss electricity system using LCA, impact pathway approach and PSA methods. The LCA method includes all energy chains from resource extraction to waste disposal and manufacturing of products and infrastructure. The human health damages are integrated to LCA in impact pathway approach and the analysis of accident risks in PSA. The sustainability evaluation framework consist of a wide range of indicators listed below.

- Environment
  - Resources: fossil energy, uranium, metals
  - Climate change: GHG and major pollutant emissions
  - Impacts on ecosystems: land use, eco-toxicity, acidification and eutrophication, land contamination
  - Waste: non-radioactive, radioactive
- Social
  - Physical security: terrorist threat, maximum number of fatalities, loss of production, cost of reconstruction, availability of disposal infrastructure, availability of disposal concept
  - Political stability and legitimacy: potential of conflicts, potential of mobilization, post operational safeguarding, proliferation, conflicts over resources, controllability of conflicts, existence of conflict resolution, mechanisms, social cooperation, trust in utility, qualitative risk, characteristics, participation of residents
  - Social development: economic development of site region, socio-economic image, impacts on local infrastructure,satisfaction of residents, equity, fair distribution of risks and benefits, electricity for economically weak groups
  - Impacts on quality of landscape and residential areas: quality of living conditions, noise impacts on residents, site dependent traffic, benefits for regional sustainability, impulses for sustainable utility behavior, impulses for sustainable consumer behavior, impacts on quality of landscape, direct land use, aesthetic impacts
  - Impacts on human health: normal operation, mortality, morbidity, severe accidents, fatalities, injured, evacuees
  - Social components of risk: perceived health risks from normal operation, accident risks, perceived health risks from accidents, perceived safety management competence, over-exploitation of renewable resources

- Economy
    - Impacts on GDP (gross domestic product): contribution to the national economy, employment, jobs in alpine/non-alpine regions, new jobs in non-alpine regions, qualification of employees, innovation, education of employees, jobs in R&D, technology transfer, development of new products and services
    - Impacts on customers: effect on electricity cost
    - Impacts on state affairs: autonomy of electricity production, cash flow to the state, external costs and benefits
    - Impacts on utility: profits, financial risks, volatility of fuel costs, risk due to authorities' interventions, necessary measures in advance and after operation, operator feasibility, liquidity, time for construction of the plant, flexibility based on marginal costs, flexibility of production, limitations in electricity production, predictability of energy availability, technical site availability, impacts on image of operator, compatibility with Axpo's corporate culture

The ranking of energy systems based on selected indicators and priorities is a straightforward method to assess pathways for transition to low carbon energy system. Asami et al. [7] rank energy systems based on their potential for climate change mitigation potential and desirability of their use in the future. The highest ranking comes for natural gas with CO_2 sequestration together with the introduction of renewable energy systems to produce hydrogen for energy storage. Edmonds et al. [44] conclude that additionally CCS technologies have a high potential to play a central role for stabilizing atmospheric GHG concentration.

The usage of nuclear energy for climate change mitigation together with renewable energy sources is assessed by many researchers. Hong et al. study on global pathways for low carbon electricity until 2060 in terms of cost and land use minimization using new policies scenario and technology database of IEA [72]. The study concludes that nuclear energy should be considered under national context by both developed and developing countries to contribute to climate mitigation together with renewable energy for climate change mitigation.

Nuclear energy investments require high capital investment which could also benefit from green financing instruments. Weisser et al. analysis of the role of nuclear energy in a future climate change agreement after the Kyoto Protocol period [190]. The study recommends that binding emission targets and CDM have potential for substitution of fossil fuels with nuclear energy whereas emissions trade cannot compensate the high capital investment cost of NPPs alone. Investments in nuclear energy requires renewal of the existing fleets in most of the developed countries whereas the developing and embarking countries consider new build projects with state of the art technologies.

1.2.3 Energy supply system and environmental impacts

This section describes the methods and tools for modeling of climate change mitigation strategies. Energy supply system comprises of all energy upstream activities including extraction and conversion of resources to primary energy and downstream activities including storage, transmission and distribution of primary energy sources to secondary and final energy demand [23]. The mathematical methods and tools either use a deductive (top-down) or inductive (bottom-up) and also their combined usage in integrated (hybrid) approach [14]. There are also alternative methods such as neural network or fuzzy logic which could be practical to use depending on their generation of consistent results [155].

The transition to a low carbon energy system requires transfer and adoption of new technologies in both industrialized and developing countries [55]. Transformation of the society to a low carbon future requires abandoning and replacement of existing rules creating new markets, players and niches which are protected from market competition and difficult to explore using linear modeling methods [118]. General and partial equilibrium models consider gradual changes in sector activities whereas there are feedback from endogenous learning and behavioral change linked with sector and infrastructural capacities.

The development of these technologies is linked with the capacity of countries to innovate or imitate technological development depending on their socioeconomic context. The incentives and capacities for transfer and adoption of these technologies could be represented either exogenous or endogenously in the methods. The gap between developed and developing countries in generation of domestic knowledge is characterized by technology frontier creating opportunity of diffusion through spill-over effect [38].

The top-down models represent the macro-economic dynamics of countries with aggregate representation of their energy systems. The bottom-up models represent energy systems of countries explicitly while the feedback from the effects on macro-economy and inter-sectoral transfers could be misguiding which could result in inconsistent results. The hybrid models capture the benefits of top-down approach such as inter-linkages in production and explicit technological representation in bottom-up approach. There are also alternative methods which are recommended and benchmarked by various researchers summarized at the end of the section.

1.2.3.1 Input-output models

I/O analysis has certain advantages for the power sector as the method represents intersectoral transactions and the production and consumption of electricity is represented primarily such as in the case study for Korea [65]. The I/O analysis proposed by Leontief provides a simple tool to assess the impacts of investments to the power sector in the short term to the economy. The model provides an opportunity to assess the direct effects to the sector where the investment is created, indirect effects from capital and labor transaction with other sectors and induced effects from the impact on consumer income.

Howells et al. [73] study uses I/O model for assessing nuclear power and nuclear technology for Korean national and regional economies. The national economy is aggregated to 36 sectors with industry disaggregated into 16 sub-sectors. The sectors related with nuclear industry sector are construction, nuclear fuel fabrication, power plant operation and maintenance whereas 29 sectors provide inputs to power plant operation sector. The household sector which is normally the ultimate driver of final demand is replaced by the nuclear industry sector. The application of the model to the Korean economy covering nuclear energy generation and radioisotope applications at the national level and construction and operation of a single NPP at the regional level shows that there is contribution of positive added value to the national economy and regional production and income together with external benefits such as avoidance of air pollution and GHG emissions by substituting fossil fuel combustion.

Geo [51] study deals with nuclear energy defining as an exogenous input in overall sectoral production with inter-sectoral linkages under general equilibrium. The final energy demand is endogenized in the model including price and quantity interactions in both directions between input and output of production. The static I/O model does not take into account the income multipliers and wage reactions which occur from disequilibrium in labor demand and supply. When an exogenous investment is injected to the model, the output changes the disposable income which is again injected to the disposable income until the economy reaches saturation.

Management of energy demand also has potential to contribute to transformation of the energy supply system to a low carbon future whereas energy intensive hot-spot production sectors should be identified for selecting technologies for climate change mitigation [188]. Technological diffusion from investments for power sector are represented by exponential learning curves for I/O coefficients which are found insufficient in Pan and Köhler study to represent endogenous technical change [138].

1.2.3.2 General equilibrium models

The structure of the economies and production capacities of sectors are assumed to be fixed in economic models whereas price changes depend on particular countries related to cost of equipment, labor costs and climate situation and combination of technologies to generate electricity from energy sources [189]. Long term modeling of the economy requires information on demographic variables, material resources and changes in structural relationships between exogenous and endogenous variables due to capital stock turnover, penetration of new technologies, emergence of alternative energy sources and sectoral shifts in energy demand.

The quantitative models using top-down approach provide explicit representation of the general economy by including the inter-sectoral linkages between production sectors. However the aggregation of the sectors makes the technological assessment of climate change mitigation options more difficult compared to the bottom-up approach which represents production technologies explicitly [186].

AIM is one of the IAMs used for quantification of the SSPs together with GCMs for projection of the radiative forcing during the 21st century. Fujimori et al. study uses AIM model to assess the SSP3 scenario which presents high levels of challenges to climate change mitigation [50]. The SSP3 can be considered as an unfavorable scenario regarding climate change whereas researchers using IAMs would need more interaction with impacts, adaptation and vulnerability (IAV) and climate model communities [110]. The results conclude that SSP3 represents high level of challenges for climate change mitigation requiring large amounts of negative emissions by 2100.

Akashi et al. study assess the technical feasibility and economic viability of RCP2.6 pathway using AIM/Enduse[Global] model as part of the EMF 27 study [2]. The scenarios use are based on GHG emissions reduction of 50% by 2050 with assumptions on the unavailability of nuclear and CCS technologies due to social or technological reasons. The study concludes that achieving the RCP2.6 target requires emission reduction in buildings and transport sectors to compensate the emission increases in steel, cement and energy sectors. Further limiting nuclear energy and CCS for larger penetration of renewable energy requires reduction in final energy demand.

However the integration of environmental and social policies with complex natural science background are difficult to represent in CGE models [14]. These policies include future phase-out of nuclear energy for larger penetration of renewable energy such as the case of Germany, renewable energy targets by issuing quotas for electricity generation and environmental tax reforms potentially leading to increase in total welfare. Rogner and Riahi study explores future nuclear pathways based on different levels of energy demand and potential global nuclear phase-out using MESSAGE [158]. The model used for the study includes energy conversion technologies from final energy to useful energy. The future role of nuclear energy is expected to depend on various factors such as energy efficiency and intensity improvements together with energy demand management. The study concludes that global phase out of nuclear energy would require massive and rapid expansion of other low carbon technologies such as renewable energy and CCS to achieve climate targets.

Bretschger and Zhang study assess market based and policy mandated nuclear phase-out policy for Swiss economy using dynamic numerical equilibrium model together with endogenous growth [21]. Particular interest is given to induced innovation effects and the structural change of the Swiss economy in the long run. The study concludes that innovation has potential to achieve ambitious climate change targets considering that regulatory frameworks should be announced at an earlier stage for perfect information of investors.

Vandyck et al. study assess the Paris Agreement climate goal using hybrid model by integrating enegry system model with CGE model [185]. The decoupling of emissions and economic growth is achieved by investment for energy efficiency improvements and maturity of low carbon energy technologies. The study concludes that the INDCs have little impact on global oil and natural gas demand as primary energy sources and there is still considerable gap between the climate goal and GHG emissions which could result from the implementation of the INDCs.

1.2.3.3 Partial equilibrium models

Partial equilibrium models with explicit representation of energy system can be used together with CGE models in order to assess general equilibrium in all commodity markets. However global economy is represented by regional production grouping countries with similar socioeconomic development and assuming inter-regional cooperation for energy and climate policy development [185]. Therefore national policies could cause large uncertainties under non-converging socioeconomic development inside these regions.

Mima and Criqui study analyses the EU energy market using POLES market simulation model under several climate change models [35]. The study focuses on the effects of climate change on heating and cooling demand with implications on cooling demand of NPPs and thermal power plants. The results show that both supply and demand sides will be affected due to more consumption of fuel for air conditioning and less for heating in residential sector whereas the operating conditions of power plants will be more difficult and costly due to increase in ambient temperature.

The usage of fossil fuels is expected to continue until 2020s with an expectation for divergence afterwards towards more cleaner, flexible, and convenient energy forms [59]. Additionally as the most stringent climate targets rely on mitigation in both energy and agriculture sectors, the IAM framework of IIASA combines these models to assess the impact of biomass supply and demand for GHG emission reductions [61]. However there are also social returns from innovative RD&D which increases the potential to invest in low carbon technologies. Grübler and Gritsevskyi study integrate MESSAGE with a multi-actor and multi-region model of endogenous technological change and conclude that the reversal of the GHG emission trend is possible only through increasing returns from investment on R&D and learning by doing [57].

Gritsevskyi and Nakicenovic study the impact of induced technological learning and uncertainties in costs of technologies and energy resources by modifying MESSAGE with scenarios generated by a selection of alternative energy system technology dynamics [56] . The study shows that different energy system structures emerge with overall energy system costs and the uncertainties together with technological learning will have the highest impact on energy system structures during the transition period to low carbon technologies.

Van Vuuren et al. study use IMAGE to assess the SSP1 as the marker scenario and compare the results with SSP2 and SSP3 elaborated by the same model [183]. One of the results requiring attention is the higher electrification of the energy system in SSP1 compared to other scenarios as a result of substitution of fossil fuels in transport, industry and buildings sectors. Sectors such as cement and steel production benefit less from energy efficiency improvements in the industry due to lack of fuel substitution capability [43]. The study concludes that the most stringent climate target is difficult to be achieved despite the significant improvements of SSP1 in access to modern energy and food, air pollution and climate change mitigation.

Calvin et al. study use GCAM to assess the SSP4 scenario by a quantitative representation of energy, land-use and land-cover and GHG emissions [24]. The results show that high income regions would allocate more land to forests as carbon sinks whereas low income regions would deforest shifting land towards more energy crops questioning whether a heterogeneous world is plausible.

Kriegler et al. study uses REMIND integrated with an agricultural model to assess the SSP5 scenario with material intensive production and consumption patterns [101]. The scenario represents very strong economic growth in GDP with the share of income spent on food decreasing by an order of magnitude. The study concludes with concerns on environmental sustainability beyond climate change due to high levels of raw material exploitation and high calorie and meat rich diet demand of the future population.

Another example of inter-disciplinary research is the Riahi et al. extension of the IIASA IAM framework by incorporating air pollution, land use and land cover change projections based on RCP8.5 pathway [152] . The RCP8.5 pathway is considered as baseline with planned air quality legislation to reduce air pollutant emissions. Policies for air pollution mitigation include measures for controlling air pollution in road transport, industrial and power plants, residential fuels for heating, international shipping and other energy upstream activities. The study concludes that air pollutant emissions could be decoupled from GHG emissions promoting local health and air pollution prevention policies in the absence of ambitious climate change mitigation targets. Also the results of the IAM study for achieving the most ambitious climate target show that air pollution benefit from climate ambition whereas additional investment is required for energy access [48].

The radiative forcing from climate change also effects the socioeconomic development and decision making for climate change mitigation and adaptation. In order to integrate these effects, the IAM community developed RCPs used by IAM and IAV communities for developing the SSPs [182]. These SSPs are also supported by policy decisions ranging from early accession with global cooperation in SSP1 and late accession by developing countries for climate mitigation efforts. There is a bidirectional relationship between socioeconomic development and climate forcing which requires the integrated modeling of these scenarios using IAMs [52].

De Cian et al. study assesses the implementation of nuclear phase-out in Western Europe to promote alternative low carbon technologies and energy efficiency using WITCH model [37]. The study shows that climate targets of UNFCCC can be achieved by long term innovation and deployment of technologies characterized by learning-by-doing.

Finally the sensitivity of these partial equilibrium models to inputs related to socioeconomic and technological data are assessed by multi-model comparison studies. Multi-model study for analysis of energy investment dynamics in the absence of a climate policy using four global IAMs and one regional energy system model points out the requirement of endogenous technological change as there are major challenges for reduction of GHG emissions by investments for low carbon technologies or increase of fossil fuel prices alone [38].

1.3 Turkish energy policy

The energy demand of Turkey is increasing at a high rate with the increase in domestic production despite efforts for energy efficiency and conservation (Figure 1.3) [121]. Investments for energy infrastructure are supported by the government as capital investments attracting direct foreign investment to the country. Meanwhile, there are certain lock-ins to fossil fuels such as natural gas used in residents, industry and power sectors and oil mainly used in the transport sector.

Total final energy demand amounts to 93.2 Mtoe in 2015. This represents 72% of total primary energy supply where the remainder is consumed by energy conversion technologies and non-energy demand. The share of industrial and transport energy demand increased with economic development of Turkey except during the global financial crisis in 2008-2009. Although residential and commercial energy demand increases with population growth and development of commercial services this increase is smaller compared to the increase in industrial and transport energy demand.

Turkey's primary energy demand is supplied from mainly oil, coal and natural gas (Figure 1.4). Most of the oil and gas is imported from pipelines and sea terminals. Although Turkey has coal reserves more than 60% of primary energy demand for coal is supplied from imported sources. Imported natural gas from pipelines was introduced as a substitute for coal burning to mitigate urban air pollution in the late 1980s. Nowadays natural gas also has the highest share in electricity production. Despite there are economically feasible hydro-power and renewable energy resources the increase in their usage is fairly slow.

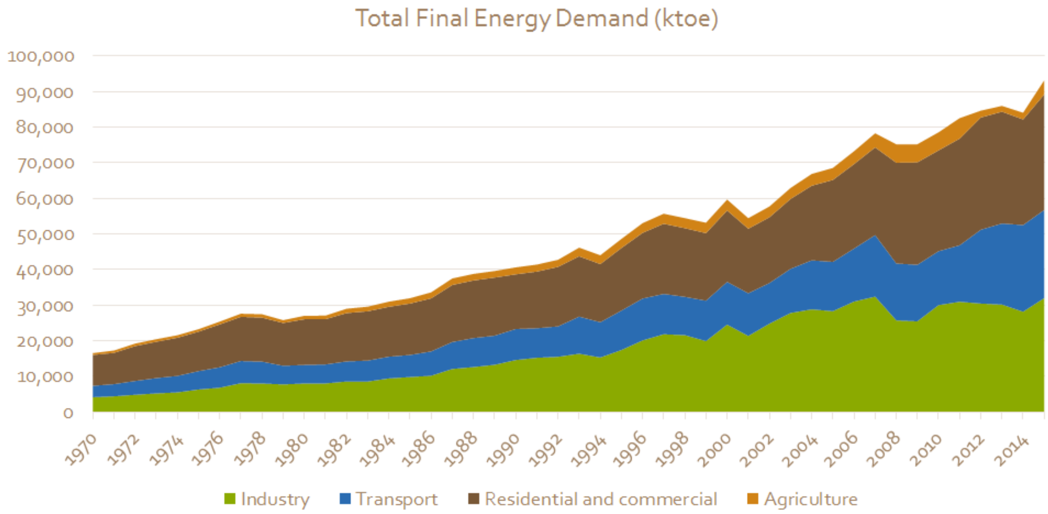

Figure 1.3: Total final energy demand

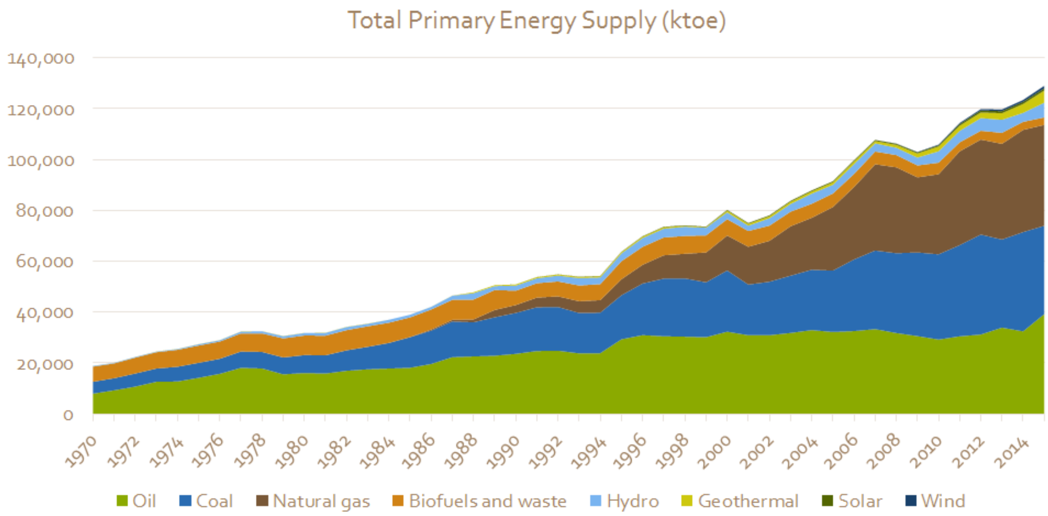

Figure 1.4: Total primary energy supply

Turkey's total GHG emissions amounts to 467.6 million ton CO_2eq in 2014 excluding LULUCF activities (Figure 1.5). The majority of GHG emissions comes from the combustion of fossil fuels in the energy sector. Therefore the trend in the increase of GHG emissions is similar to the trend in the increase of the total final energy demand. Den Elzen et al. [42] review of GHG emissions in major emitting countries and regions show that Turkey is likely to achieve the INDC target which can be increased by more ambitious efforts for the most stringent climate targets.

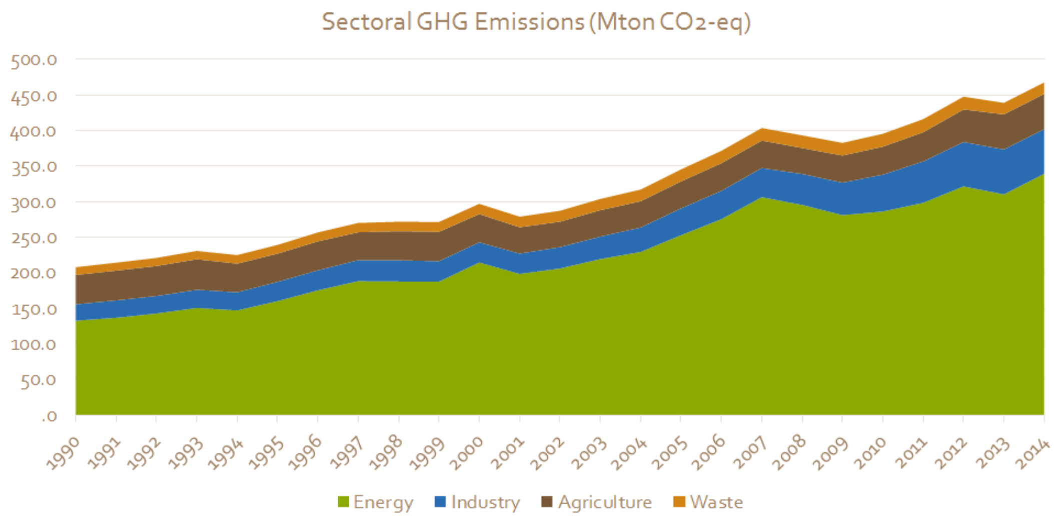

Figure 1.5: Sectoral GHG emissions

The national government policy includes the diversification of primary energy resources and energy markets, reliability of energy imports and reduction of energy costs to strengthen energy security [45]. Climate change mitigation strategy depends on financing mechanisms of the UNFCCC whereas Turkish strategy also includes a higher supply of domestic fuels such as hard coal and lignite [149]. The diversification of primary energy sources includes commissioning new nuclear power plants with Akkuyu NPP currently constructed by Rosatom and agreements with other countries for additional investments [75].

The most important environmental benefit of nuclear energy is the generation of electricity with no GHG emissions during operation. The energy sector has the largest share of GHG emissions with more than 70% of total GHG emissions in Turkey.

Nuclear energy generating base-load electricity with high energy intensity has the potential to mitigate GHG emissions from the energy sector by substituting other base-load electricity generation technologies such as coal, oil and natural gas-fueled power plants.

Despite the economic and environmental impacts, nuclear energy is also under debate regarding sustainability with concerns on nuclear reactor safety, disposal of radioactive wastes, proliferation risk of nuclear weapons and availability of nuclear fuel resources and economic competitiveness of nuclear energy in the electricity market [137]. However, the costs and benefits of nuclear energy are assessed using economic, environmental and social indicators with various methodologies including LCA, MCA or IAM studies.

There are studies in the literature which assess the relationship between nuclear energy and economic development on a national or regional framework focusing on either economic development or climate change mitigation. However the objectives of these studies differ on a wide range with expansion of nuclear fleets such as in Korea [194] or closure of NPPs such as in Japan [191]. Utilities in countries with long-term experience of NPP operation and with no ambitious expansion plans focus on socioeconomic impacts of nuclear energy in order to justify their future operation such as in USA [129] and in Canada [26].

The climate change mitigation strategy of Turkey for the first commitment period of the Paris Agreement for the energy sector includes nuclear energy generation together with increased use of renewable energy resources, reduction of electricity transmission and distribution losses, refurbishment of old electricity generation power plants, and the introduction of innovative technologies such as micro-generation or co-generation systems [149]. As the nuclear energy program of Turkey progresses, there is an increasing requirement to assess the role of nuclear energy to the climate change mitigation strategy in order to quantify the contribution.

The general energy policy of Turkey focuses on the supply of secure, sustainable and affordable energy by diversifying energy supply routes and source countries, promoting usage of domestic resources and increasing the energy efficiency and renewable energy usage to decrease the energy intensity of production [78]. Nuclear energy is considered for diversification of electricity generation and also for mitigation of GHG emissions from energy sector. The key characteristics of Turkish energy policy are listed as below.

- Increase domestic resources
- Decrease energy import
- Diversification of supply sources
- Oil and gas pipeline and storage projects
- Increase energy efficiency and renewable energy usage
- Improve competitiveness in electricity and natural gas markets
- Introduce nuclear energy for electricity generation

There are various studies in literature which assess the potential of climate change mitigation in Turkish power sector for determining the national commitment to the UNFCCC. Ari and Yikmaz study assess the potential of renewable energy sources for Turkey in order to meet the commitment of 21% GHG emission reduction by 2030 compared to BAU [6] . The study uses national accounts and general energy balance tables of Turkey and calculates emissions using IPCC Tier-1 methodology. However there are important specifications of Turkey's electricity generation system such as the high peak demand during certain periods and technical losses in the grid reaching 20% on average which varies greatly between regions.

Boran et al. study assess the ranking of electricity generation systems based on MCA method using total generation cost, GHG emissions, energy efficiency and acceptability for Turkey concluding nuclear energy ranking second after hydro-power excluding acceptability and third after including acceptability [16]. Karaveli [92] further compares Akkuyu NPP with planned solar PV power plant in Karapinar based on material cost analysis showing that solar PV has lower cost when land costs are excluded however NPP has higher energy density per materials consumed in their construction.

Kat [95] developed CGE model for Turkey's energy system development based on GTAP-Power database for assessing the impact of GHG emission reductions on GDP.

The annual changes of primary energy supply are constrained in order to conserve the historical consumption trends. The result shows that the impact of GHG emission reduction to GDP is very low as a result of renewable energy capacity of Turkey. The scenarios are based on INDC submissions of Turkey and national accounts which could be affected by global pathways represented by SSPs and carbon feedback from RCPs. This effect is also represented by Aydın [9] whereas there is also opportunity to use carbon tax revenues for transformation of the energy sector.

1.4 Hypothesis and research questions

The study is done as part of the IAEA CRP on the assessment of the potential role of nuclear energy in mitigating climate change. The investigations focus on the assessment and effectiveness of support mechanisms (ie. domestic policies, carbon pricing) recognized under the Paris Agreement in order to identify key barriers and develop approaches to address investments in low carbon technologies, including nuclear energy. MESSAGE is used for energy system modeling and assessment of energy policies including emission taxes and FITs. The model is distributed by the IAEA to Member States free-of-charge in research for non-profit purposes [76].

A set of analytical IAEA tools or Member States' own models or tools are combined, tested and applied to assess the potential role of low carbon electricity generation projects, including nuclear energy, within long-term national GHG mitigation strategies. The variety of starting points and national circumstances provided opportunity to both developed and developing Member States to share information in identifying least-cost decarbonisation strategies.

Developed and developing states need to design the implementation of INDCs and prepare their mid-century, long-term low GHG emissions development strategies under the Paris Agreement of the UNFCCC. The overall objective of the CRP was to support Member States in national level evaluations on the potential role of nuclear power in GHG mitigation in preparation of their low GHG emissions development strategies under the Paris Agreement. Another important objective was to develop analytical framework for the assessment of support mechanisms to address investments in low carbon technologies, including nuclear.

Although the Paris Agreement combines efforts of countries for achieving climate targets, it is also criticized by various researchers as developing countries are generally allowed to emit GHGs as much as they assess their capacities for climate change mitigation [25]. Also the impact of transnational initiatives in addition to the efforts of UNFCCC are considered as too low to achieve the most stringent climate targets [119]. On the other hand developing countries emphasize the principles of CBDR and RC for taking action against climate change [71]. There are also regional differences considering the IAM from climate change which could prioritize climate change adaptation measures in many countries leading the inefficient allocation of global resources [170].

The mechanisms to promote the participation of developing and least developed countries are assessed by various researchers. The participation of developing countries on socioeconomic development strategies based on climate change adaptation and mitigation is important to assess climate change vulnerabilities [123]. Bosetti et al. study furthers show that the delayed participation of developing countries to climate change mitigation and inclusion of external costs to energy investment decisions is necessary and barriers in technology adoption and diffusion of these countries should be taken into consideration during the implementation of the Paris Agreement [18].

The research questions which are explored in this study are listed as below.

- What are the impacts of future socioeconomic development forecasts on the penetration of nuclear energy for low carbon transition of the energy sector?
- How does the primary energy resource costs effect the development of the energy supply system to supply the final energy demand?
- What are the requirements for robustness of the electricity grid system for penetration of intermittent renewable energy resources to the energy system?
- What are the impacts of climate policies in the energy system such as carbon taxes and FITs for renewable energy investments?
- How does the decision makers assess the climate change mitigation strategies

and low carbon transition of energy system?

The activities of the CRP in the first year included the preparation for the quantitative study for the energy system development. The literature on the development of energy sector and climate mitigation for Turkey was assessed for selection of scenarios to be used for the study. The data on energy activity and capacity of the sectors for the reference year was collected using national accounts and international studies.

The activities for the second year focused on the quantitative assessment of the energy system development in Turkey. The energy system model was developed based on the baseline scenario with linkages to the economic and environmental impacts using selected indicators. Baseline scenario represents the existing policies of Turkey for economic and energy system development including the legislation for environmental emissions. The results of the model were checked using sensitivity analysis for the major assumptions used in the scenarios.

The activities for the final year focused on the introduction of low-GHG emitting technologies and possible incentives for decarbonization of the energy sector in Turkey. The costs of these mitigation methods were assessed by providing linkages with the socio-economic indicators. The results of the model were checked using sensitivity analysis for the major assumptions used in the scenarios. The social dimension related to preferences for energy policies were integrated to the study by using an expert elicitation survey and analyzing the relations between values and energy policy choices of participants.

This study focuses on the assessment of the potential role of nuclear energy for climate change policies of developing countries with a case study for Turkish energy system development. Based on the literature review and in relation with the research questions explored during the IAEA CRP, this study assesses the hypothesis listed in Table 1.2.

Research methodology is presented in Chapter 2 including the assessment of energy and climate scenarios, the modeling methodology used for the energy system development with socioeconomic and technological input data, the externalities related to electricity supply system investments including atmospheric emissions and flexibility

Table 1.2: Hypothesis tested in this study

Hypothesis	Description
I	In a policy for promotion of renewable energy sources, the penetration of nuclear energy depends on the increase in the final energy demand and economic development.
II	The increase in final energy demand would result in increase of marginal prices of electricity production resulting in higher penetration of nuclear energy as low carbon energy source.
III	FITs for power generation from renewable energy sources requires nuclear energy for transition to a low carbon energy system in the long term.
IV	Energy policy makers are sensitive to climate change mitigation although the prioritization is for energy security with utilization of domestic energy resources.

requirements of the grid system and final discussion of potential climate feedbacks to the energy system. The results of the study are analyzed in Chapter 3 for energy system modeling, expert elicitation, sensitivity analysis of results and validation of the research hypothesis. Finally Chapter 4 discusses the overall results of climate and scenario exploration by integrating the modeling results with preferences of experts using MCA tool developed by Bigaret et al. [13].

CHAPTER 2

RESEARCH METHODOLOGY

2.1 Energy and climate scenarios

The IPCC SRES was based on the economic development as the driving force of emissions and the level of global collaboration for emission reduction [127]. These scenarios are classified as A1 and A2 focusing on economic development and B1 and B2 considering environmental consciousness with the expense of economic development. A1 and B1 scenarios assume global cooperation for development whereas A2 and B2 scenarios consider interregional differentiation in socioeconomic development. These scenarios were additionally divided to sub-scenarios covering a range of GHG emissions from carbon intensive development to decarbonization of the economy.

Before the preparation of IPCC AR5, there was a need to develop common scenarios in order to combine different communities involved in climate mitigation and IAV [178]. These scenarios are based on two independent axis with SSPs based on narratives for future global development and RCPs based on future radiative forcing from increasing carbon concentration in the atmosphere [153]. The SSP narratives and development methods describe the future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, environment and natural resources in the world [134].

The narratives of SSPs are based on the level of challenges to climate mitigation and adaptation [142]. SSP1 represents low challenges to mitigation and adaptation with dominance of biospheric values and international cooperation. SSP3 represents high challenges to mitigation and adaptation with dominance of egoistic values and regional rivalries. SSP2 represents medium challenges to mitigation and adaptation with uneven development partially representing SSP1 and the others SSP3. There are also unsustainable pathways with increasing inequality leaving the most vulnerable having high challenges to adaptation for SSP4 and techno-centric development with increasing use of fossil fuels having high challenges to adaptation for SSP5.

The quantification of these SSPs was done by modeling communities in Table 2.1 using different socio-economic projections and carbon concentration pathways represented by RCPs. The RCPs range from radiative forcing of 2.4W/m2 having peak emissions in the middle of the century and 8.0W/m2 with increasing emissions until the end of the century. This method provides a common framework for both climate - earth system communities and energy - environment economists to further explore shared policy actions to achieve the climate change target of the Paris Agreement with 2 °C surface temperature increase by the end of the century and also considering further ambition to reduce this to 1.5 °C.

Table 2.1: Models used for quantification of SSPs

Model	Institution	Model category	Focus
AIM [50]	NIES	CGE	Whole economic production and consumption, emphasis on energy to assess the related GHG emissions
GCAM [24]	PNNL	IAM	Market equilibrium model, interactions with global economic, energy, agricultural, land use and technology systems, emphasis on human earth systems
IMAGE [183]	PBL	IAM	Environmental impacts of energy demand, production of primary and secondary energy and related GHG emissions
MESSAGE [152]	IIASA	IAM	Linear energy system optimization, interactions with land use based activities
REMIND [101]	PIK	IAM	Integrating macro-economy, energy system, and land-use and climate modules with agricultural sector
WITCH [17]	FEEM	CGE	Coupling of top-down economic model with representation of the energy sector with medium complexity

The higher climate ambitions for limiting temperature increase to 1.5 °C by the end of the 21st century requires major social transformations to decouple welfare from energy demand [61]. The transformation is from welfare maximization to comfort optimization which is based on convergence of society energy and nutrient needs having knock-on effect on upstream production activities. Digital transformation plays a critical role as many devices we use today have made substituted the energy intensive equipment we used only a decade ago such as cameras and VCD/DVD players.

In this study the SSPs are selected in the sustainable development range from SSP1 to SSP3 with baseline scenarios with emission penalty costs for air pollutants SO_2 and NO_x. The mitigation scenarios for RCPs include increasing costs of carbon emissions as a result of carbon taxes which are utilized for subsidizing renewable electricity generation with FITs [54]. The marginal costs of FGD for SO_2 emissions and SCR for NO_x emissions assessed for Turkey are used for both Baseline and climate mitigation scenarios [145].

Carbon taxes are simple and straightforward policy instruments for internalizing the costs of GHG emissions in order to overcome the market failure of common and free-rider problem of public goods [99]. However the determination of a carbon price is difficult and challenging to reduce global emissions as the GHG intensive sectors have the chance to pay the costs and continue their production without any abatement. Furthermore cap-and-trade mechanism has higher public acceptance especially in the USA as the price mechanism of the market remains undisturbed.

However ambitious targets for GHG emission reduction are difficult to be achieved only by carbon taxes as markets lacking transition would still favor activities with high emissions [40]. Additional climate policies for reduction of GHG emissions include incentives and subsidies for low-carbon energy transformation as listed below.

- Power generation
  - Carbon emission allowances [68]
  - Availability of nuclear energy and CCS as backstop technologies [32]
  - Gradual ban on coal power plants without CCS [40]
- Road transport

- Subsidy for electric and hybrid vehicles [130]
  - Fuel efficiency and emission standards [20]
  - Subsidy for electric trains and biofuels for air travel [114]
- Residential energy demand
  - Carbon tax on residential energy usage [36]
  - Subsidy in advanced heating and cooling technologies [85]
  - Subsidy for residential use of small solar PVs [93]
  - Energy savings for household appliances [1]
- Industry energy demand [43]
  - Carbon tax or emission constraints on industrial energy usage
  - Fuel substitution for cement production
  - Subsidy for electric arc furnaces in steel industry

The technical and economical variables used for scenarios based on socioeconomic and climate conditions are taken from SSP and RCP databases for IPCC [180]. These variables are results of IAM studies for global climate change until the end of the 21st century by aggregating the global development into socioeconomic and geographic regions. The linkages between socioeconomic and energy system development and carbon concentration (Figure 2.1) is provided with costs for carbon emissions which is defined as carbon emission penalty for the power sector in energy system model from initial year of 2015 to 2050 as the second commitment period of Paris Agreement [50].

The model includes load regions for separation of daytime which is used to separate the load inputs from wind and solar power. Wind power is assumed to generate during morning and evening load regions and solar power during midday region.

Renewable energy depends on environmental conditions requiring suitable regions with necessary wind speed for wind power, high elevations for river flow for hydropower and constant elevations with necessary solar insolation for solar power. The model includes seasonal and diurnal load curves for wind and solar power which

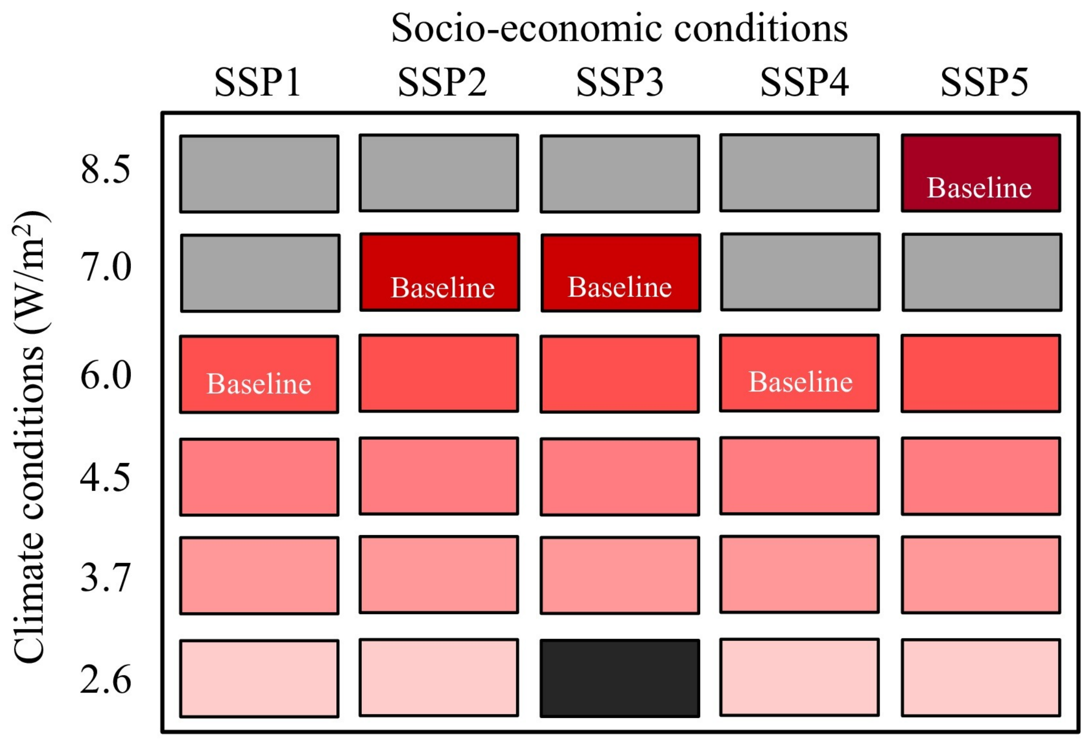

Figure 2.1: Mapping of SSP and RCP conditions for scenario development

determine the load factors of their availability [168]. Renewable energy load regions are selected as Konya for solar energy, Izmir for wind power and Erzincan for hydro power (Figure 2.2). Monthly load data for solar, wind and hydro-power are elaborated for these locations from NASA Langley Research Center POWER project database [1].

Assumptions for daily load variations in wind and solar power are based on their intermittency and the requirement to prevent their competition for the same load regions. Solar input load is full during noon hours and wind power is full during morning and evening. The main reason for this approximation is the physical basis of solar power availability and the intention to prevent competition with wind power for final electricity demand. Electricity generation from wind power in Turkey is mainly utilized in Western regions with assumption for diurnal slope generated between the sea and the land. The coastal regions are surrounded by mountains causing diurnal mountain wind which reverses direction twice per day. Hydro power is used both for supplying final electricity demand and also ancillary services including grid flexibility. Therefore the input load variation of hydro power is only dependent on seasonal variation of ROR flows.

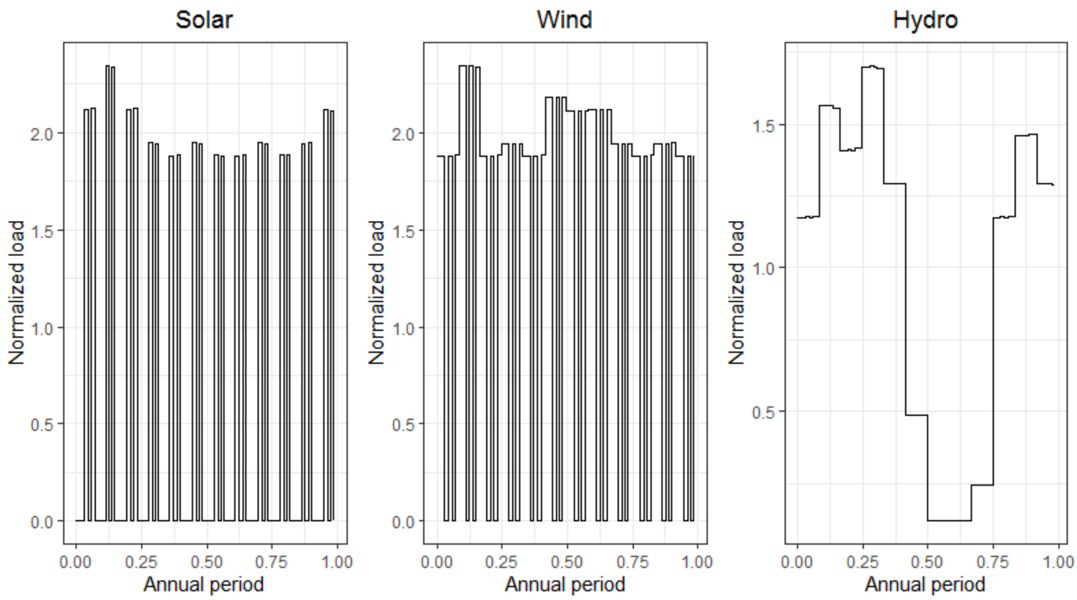

Figure 2.2: Input load curves for solar, wind and hydro power

[1] These data were obtained from the NASA Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science/Applied Science Program.

MESSAGE is a linear optimization model, developed by IIASA and distributed by IAEA to Member States, which is primarily used for medium-to-long term energy system planning, policy analysis and scenario development [77]. The energy flows are represented as energy chains starting from resources, imports and exports, primary energy, secondary energy, final and useful energies such as light, space heating, rotary motion and travel distance. The energy system is optimized under user defined constraints such as GHG emissions, emission penalties, ROR, land availability and addition of installed capacity.

The matrix generator module of MESSAGE converts the energy system variables as columns and relationships as rows of the linear optimization problem matrix. The energy system variables consist of energy flows representing activities, power representing capacities and stock-piles representing the temporal storage of energy. The constraints representing the boundary conditions of linear problem in time are represented as energy flow balances from resource extraction to final utilization, cumulative or relative activity constraints on an annual or cumulative basis and dynamic constrains setting relations for activities between two consecutive periods.

Energy conversion technologies are defined by using variables for their activities and capacities in a period. The activities represent energy flows whereas energy carriers like electricity and hydro-power are defined with load regions to represent hourly, weekly or monthly variations. Higher penetration of renewable energy technologies such as hydro-power and biomass also have impact on water and land resources which can be more pronounced for high energy and fossil fuel demand growth [124]. The capacities represent the power of energy conversion technologies whereas technologies could also be modeled without capacity variables.

The energy demand is supplied with installed capacity multiplied by capacity factor for technologies without load regions. Energy conversion technologies can use varying or multiple energy inputs and outputs. For technologies with load regions the energy demand is supplied by activity variables generated separately for each load region. The resource variables are defined as energy flow variables which define their annual extraction. Resources can also be categorized under separate cost categories defined by their grades. Storage of fuels or hydro-power are defined as stockpile variables giving the opportunity for storing on low demand and converting to other energy carriers on high demand. There are also specific requirements for some energy sources such as storage constraints for hydropower or cooling requirements for nuclear fuel.

Dynamic linear optimization model MESSAGE is used for analysing the energy supply system development from 2015 to 2050 for baseline scenarios represented by SSP1 to SSP3 and mitigation scenarios by including carbon prices from IAM benchmark studies of SSPs with respect to RCPs [180]. The technology options include energy conversion technologies from resources to primary energy (resource extraction/import), secondary energy (electricity, oil products) and final energy for electricity, heat and non-energy demand.

The emission factors are taken from GEA study of IIASA for final energy demand. Life-cycle emission factors are used for electricity generation assuming additional carbon emissions from construction and land use for renewable energy investments and fuel cycle from nuclear power investments. The externalities related to air pollutant emissions of SO_2 and NO_x are included as damage costs in the model [96]. The general structure of modeling inputs and outputs are given in Figure 2.3.

Figure 2.3: Energy system modeling using MESSAGE

Final energy demand for SSPs are calculated as exogenous input to model by Kaya

Identity Decomposition (Equation 2.1) using OECD forecasts for population and GDP and aggregate energy intensity (Energy/GDP) results of IAM studies for SSPs. Energy resource potentials of hard-coal and lignite are defined whereas oil and natural gas resources are neglected as their production is non-significant compared to their total primary energy demand. Electricity demand includes seasonal and daily affects whereas residential heating is defined with monthly loads taken from previous applications of MESSAGE for assessment of natural gas storage in Turkey.

$$CO_2 = Population \cdot \frac{GDP}{Population} \cdot \frac{Energy}{GDP} \cdot \frac{CO_2}{Energy} \tag{2.1}$$

The inputs for calculating the energy demand from Kaya Identity equation are included from the literature and databases listed below.

- SSP narratives and assumptions from Bauer et al. (2017) [10]
- Population and GDP projections from SSP database [83]
- Energy intensity of production for SSPs from Fricko et al. (2017) [49]
- Carbon prices from global IAM studies based on RCP database [80]

Table 2.2: Final energy demand in SSP1 scenarios

Years	Population (million person)	GDP-PPP (billion US$@2005)	Final energy demand (MWyr)
2015	75.91	1139.45	117320.00
2020	79.81	1400.13	127538.95
2025	81.49	1697.00	136758.85
2030	84.35	2035.82	145148.77
2035	85.38	2410.22	152030.27
2040	86.99	2804.26	156491.28
2045	87.60	3193.05	157643.74
2050	87.35	3558.19	155417.09

Technology options include existing baseline and potential mitigation options which are considered to be available in the medium term until 2050. These include renew-

Table 2.3: Final energy demand in SSP2 scenarios

Years	Population (million person)	GDP-PPP (billion US$@2005)	Final energy demand (MWyr)
2015	76.79	1145.46	117320.00
2020	81.01	1413.62	131007.74
2025	83.83	1691.51	141843.26
2030	87.77	1976.55	149972.31
2035	89.77	2269.88	155839.18
2040	92.75	2584.29	160541.45
2045	94.62	2910.04	163574.08
2050	95.88	3243.90	164988.46

Table 2.4: Final energy demand in SSP3 scenarios

Years	Population (million person)	GDP-PPP (billion US$@2005)	Final energy demand (MWyr)
2015	77.50	1153.36	117320.00
2020	82.62	1431.10	139166.32
2025	86.86	1682.01	156367.98
2030	92.42	1902.17	169054.80
2035	96.22	2099.39	178372.35
2040	101.00	2294.49	186370.62
2045	105.58	2481.96	192726.70
2050	109.23	2664.26	197778.91

able energy technologies in the electricity sector, biofuels in the transport sector and nuclear energy with constraint of maximum one reactor unit commissioned in a selected year due to strict safety regulations.

Emission factors are for CO_2 as climate forcing and SO_2, NO_x and particulate matter as air pollutants [113]. Electricity sector CO_2 emission factors are used as life-cycle emissions from GEA [81] as new capacity additions result in additional emissions from land-use, construction and fuel extraction-manufacturing. CO_2 emissions for final energy demand are taken from national submissions of Turkey to UNFCCC. Fossil fueled power plants have options to run with or without filter based on the marginal costs of SO_2 and NO_x emissions.

Final energy demand are calculated based on population and GDP projections and results of energy intensity of production from IAM studies of SSPs. This method is similar to the Triptych approach where the energy intensities of industry, residential and power sectors converge relative to historical activities [68]. GDP projections are based on conditional convergence of development with total factor of productivity increasing faster in developing countries than developed countries [41]. These projections are calculated separately for specific (electricity) and non-specific (heat) energy including rates of electrification in residential and transport sectors and feed-stock use.

Electricity grid flexibility to supply peak demand in all load regions is represented by user defined constraint where fossil fueled power plants make positive contribution and renewable energy (solar and wind) make negative contribution due to their intermittent. These are provided exogenously to the model whereas the transition of energy system will have feedbacks to flexibility requirements which are difficult to represent with linear constraints [55]. Fossil fueled and nuclear power plants also include ramping factors for increasing or decreasing their powers due to thermodynamic efficiencies for fossil fuels and neutron parameters for nuclear energy.

Energy resource potential include fossil fuel reserves which could be extracted during the modeling horizon and renewable energy sources which are feasible to utilize. Hard-coal and lignite are defined as fossil fuel reserves as natural gas and oil amounts are negligible compared to their demand in Turkey. The rate of change in the increase and decrease of hard-coal and lignite has constraints providing relatively stable time preference for these fuels during the modeling horizon. Natural gas is imported but represented with gas pipelines resulting in capital investment for supply of this fuel. Oil is imported both by crude oil and also oil products produced by refineries in Turkey whereas possible deficit of oil products are supplied by import.

Energy demand load is characterized by seasonal and weekly effects whereas season is represented by 12 months and weeks are represented by 3 load zones for workdays (maximum-average-minimum) and 2 load zones for weekends and holidays (high-low). This results in total 60 load regions for final electricity demand. Load regions for residential heating are represented with only seasonal effect. Hydro-power is supplied from river run-off based on precipitation loads in Eastern Turkey with major hydroelectric dams. Natural variability of flow is represented by ROR load regions which are controlled by storage to supply the demand load for electricity [46]. Solar and wind inputs maximums are arranged in different periods (solar during daytime, wind during morning and evening) so they do not compete for low-carbon electricity demand.

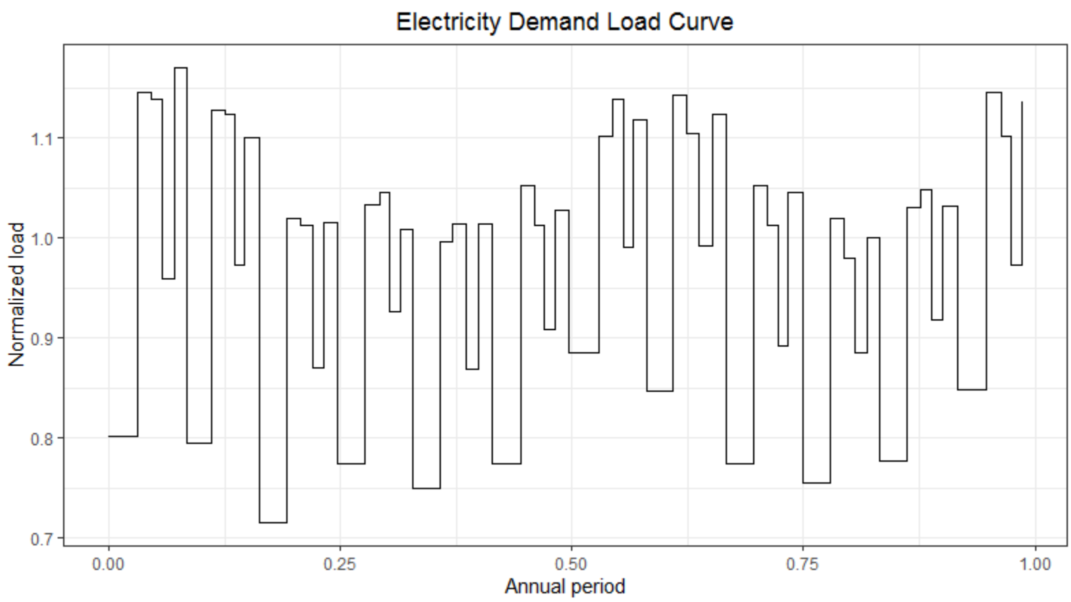

Figure 2.4: Final electricity demand normalized load curve

The final natural gas demand is also effected by seasonal variation of weather as natural gas is widely distributed for power, industrial and residential demand in Turkey [79]. During winter demand for natural gas increases for heating in residential dwelling and in summer in power sector for air conditioning and additional refrigeration demand (Figure 2.5). Unlike electricity, natural gas can be stored under geological formations and inside pipelines in order to protect the gas market from price volatility and demand peak fluctuations. However the volume of natural gas storage is assumed to be negligible compared to annual final energy demand as local production volume is also very small [79]. The annual capacity factor of final natural gas demand is calculated to be 70% in MESSAGE inter-phase for the modeling solver.

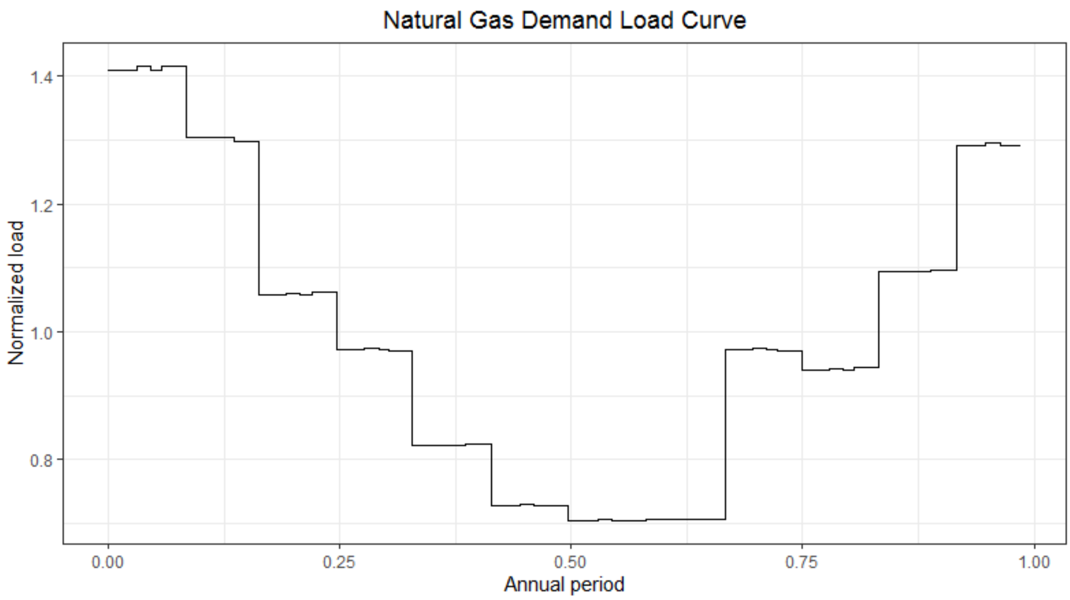

Figure 2.5: Final natural gas for residential heat demand normalized load curve

One of the main reason to include a natural gas demand load curve for final energy is the elasticity of substitution with natural gas for power sector. Primary natural gas is both supplied to power sector and also distributed for final energy demand which is price elastic. Final energy demand for natural gas is defined exogenously effecting the primary natural gas supply for power sector. The seasonal variability of final natural gas demand provides a more realistic situation for the primary natural gas seasonal availability for the power sector.

The seasonal, daily and hourly variations of electricity demand are defined by using the load data from Ministry of Energy and Natural Resources [122] database which are simplified for usage in MESSAGE. The electricity demand load is generalized for three regions during workdays and two regions during weekends and holidays for all seasons (Figure 2.4). The electricity demand load is normalized to annual final electricity demand increasing in winter for additional heating and in summer for increasing air conditioning and refrigeration requirements. The annual capacity factor of final electricity demand is calculated to be 85% in MESSAGE inter-phase for the modeling solver.

2.2 Energy supply system modeling

MESSAGE is a linear optimization model for assessment of the energy supply system development to supply the energy demand based on constraints related to technical capacities of power plants, feasible capacities of renewable energy technologies, the installed capacity in the reference year and market penetration rates of primary energy supplies. The model is used in this study to minimize the total discounted energy system cost from 2015 to 2050 using 5 year intervals using the social discount rate assessed by Halicioglu and Karatas [64]. The GLPK solver together with MESSAGE uses iterative method solving both the primal and dual solutions simultaneously and providing the optimization results with their ranges inside the feasible region [53].

The objective function (Equation 2.2) is denoted by z calculated by the linear multiplication of c including costs and x including the levels of activities. The equations used in the problem are constructed as the rows with technology variables dispersed as the columns of A. The solver calculates the activities of energy conversion technologies x from resources to final energy demand in order to satisfy the right hand side constraint denoted as b. Slack variables λ_j are included by the solver with zero activities to convert the inequalities into equality constraints.

$$\begin{aligned} min. \longrightarrow z &= \underline{c}_j^T * \underline{x}_j \\ s.t. \longrightarrow \underline{\underline{A}}_{ij} * \underline{x}_j &\geq \underline{b}_i \\ x_j &\geq 0 \,\forall j \end{aligned} \tag{2.2}$$

The dual solution function (Equation 2.3) is denoted by *w* calculated by the linear multiplication of right hand side constraint denoted as *b* and utility of using these resources *u* which are considered as scarcity rent of using these resources. The equations used in the dual problem are constructed as the vector multiplication of scarcity rents related to equations of primal problem constraints (Equation 2.2) and technology variables dispersed as the columns of *A*. The solver calculates the shadow prices of energy of the inputs to the energy conversion technologies *u* in order to satisfy the costs of input activities of energy conversion technologies *c*.

$$\begin{aligned} max. \longrightarrow w &= \underline{b}_i^T * \underline{u}_i \\ s.t. \longrightarrow \underline{u}_i^T * \underline{\underline{A}}_{ij} &\leq \underline{c}_j \\ u_i &\in \mathbb{Q}\,\forall i \end{aligned} \tag{2.3}$$

The GLPK solver used by the MESSAGE model calculates the primal and dual problems iteratively searching for convergence of both solutions using Kuhn-Tucker conditions [14] for characterizing the optimality of the linear program (Equation 2.4).

$$\begin{aligned} \underline{u}_i^T * \left(\underline{\underline{A}}_{ij} * \underline{x}_j - \underline{b}_i\right) &= 0 \\ \underline{\lambda}_j^T * \left(\underline{u}_i^T * \underline{\underline{A}}_{ij} - \underline{c}_j\right) &= 0 \\ \lambda_j &\geq 0\,\forall j \end{aligned} \tag{2.4}$$

General energy balance table is used for defining energy system structure from primary energy to final energy sources. Energy demand projections are calculated using Population and GDP projections from SSP database hosted by IIASA [180] and reductions in energy intensity of productions for SSPs. The natural resources are hardcoal and lignite where local oil and gas resources are neglected due to their very low shares. Policy constraint is defined for nuclear energy where safety regulations are strict and therefore for each modeling year maximum one reactor unit is permitted to be commissioned.

The selection of the discount rate is an important assumption based on the importance given to the benefits of the future generations. The discount rate should also be consistent with the real interest and savings rates in the market to answer question on the quantity, speed and cost of investments required for climate change mitigation and adaptation [131].

All costs related to the activity and capacity addition of energy conversion technologies are discounted to the first year of the modeling period in the objective function (Equation 2.5). Discounting of activity costs are done from the beginning of the year whereas capacity investment costs are discounted from the middle of the year to the initial modeling year. The technologies convert energy forms starting from resources to primary energy, secondary energy (electricity) and final energy with inputs given exogenous based on Kaya Identity Decomposition of data from SSP database hosted by IIASA [180].

Load regions are defined for input of intermittent renewable sources (hydro, wind and solar) and final demand for electricity and residential heating. The user defined relations calculate the costs of environmental emissions SO_2 and NO_x for all scenarios and CO_2 for scenarios with climate targets defined by RCPs. Investments for new capacity additions are split in half completed before commissioning and the remaining half following commissioning of the units. User defined relations are only related to the activities of energy conversion technologies and local capacities of fossil and renewable resources are defined as activities.

$$\sum_{r}\sum_{t}\left[\beta_m^t \Delta t \sum_{zsvd}\sum_{lll}\left\{zsvd....rrllltttt \times \epsilon_{zsvd} \times ccur(zsvd,t)+\right.\right.$$
$$\sum_{i=1,2,c}\sum_{m} rho_{zsvd}^{mlt} \times cari(ml,t) + \sum_{zsvd}\sum_{\tau=t-\tau_{zsvd}}^{t} \Delta\tau \times yzsvd..\tau \times cfix(zsvd,\tau)+$$
$$\left.\sum_{g}\sum_{l}\sum_{p} rzrg....rrllltttt \times cres(zrg,t)\right\}+$$
$$\beta_b^t \Delta(t-1)\sum_{zsvd}\sum_{\tau=t}^{t+t_d}\left\{yzsvd...rr...\tau \times ccap(svd,\tau) \times fri_{zsvd}^{t_d-\tau}+\right.$$
$$\left.\left.\sum_{i=1,2,c}\sum_{m} rc_{zsvd}^{mt} \times cari(m,t) \times fra_{zsvd,m}^{t_d-\tau}\right\}\right] \longrightarrow min$$
$$\beta_b^t = \left[\frac{1}{1+\frac{dr}{100}}\right]^{t-t_0}, \beta_m^t = \left[\frac{1}{1+\frac{dr}{100}}\right]^{t+\frac{\Delta t}{2}-t_0}, \tag{2.5}$$

Energy demand is defined exogenous in the model based on the calculation using Kaya Identity Composition to socio-economic indicators given in SSP database hosted by IIASA [180]. Primary solar and wind energies have load regions complementing each other by favoring solar during sinking of the air (passive weather) and wind during rising of the air (active weather) (Equation 2.6). Final electricity has hourly load regions whereas final gas and residential heat has monthly load regions to represent the effects of temperature change between seasons. Load regions for primary and secondary energy sources are summed up to calculate the final energy demand without load regions (Equation 2.7).

$$\sum_{sv} \epsilon_{zsvd} \times zsvd....rrllltttt + \sum_{sv} \beta_{zsv\delta}^{d} \times zsv\delta....rrllltttt \geq D_{drlt} \tag{2.6}$$

$$\sum_{l}\sum_{sv} \epsilon_{zsvd} \times zsvd....rrllltttt + \sum_{sv} \beta_{zsv\delta}^{d} \times zsv\delta....rrllltttt \geq D_{drt} \tag{2.7}$$

Energy balance equations are for all energy levels for final specific (electricity) and non-specific (heat) energy demand. For nuclear fuel cycle energy balance equations

Table 2.5: Definition of objective function variables

dr	discount rate in percent,
$zsvd....rrlllttt$	annual consumption of technology $zsvd$ of fuel s load region l and period t,
ϵ_{zsvd}	efficiency of technology $zsvd$ in converting s to d,
$ccur(zsvd, t)$	variable operation and maintenance costs of technology $zsvd$ (per unit of main output) in period t,
rho_{zsvd}^{mlt}	relative factor per unit of output of technology v for relational constraint m in period t, load region l,
$car1(ml, t)$	coefficients for the objective function, that are related to the user defined relation m for load region l in period t,
$yzsvd...rr...ttt$	annual new built capacity of technology $zsvd$ in period t,
$cfix(zsvd, t)$	fix operation and maintenance cost of technology $zsvd$ that was built in period t,
$ccap(zsvd, t)$	specific investment cost of technology v in period t (given per unit of main output),
fri_{zsvd}^{n}	share of this investment that has to be paid n periods before the first year of operation,
rc_{zsvd}^{mt}	relative factor per unit of new built capacity of technology $zsvd$ for user defined relation m in period t,
$fra_{zsvd,m}^{n}$	share of the relative amount of the user defined relation m that occurs n periods before the first year of operation,
$rzrg....rrlllttt$	annual consumption of resource r, grade g in load region l and period t,
$cres(rgpl, t)$	cost of extracting resource r, grade g, elasticity class p in period t and load region l

Table 2.6: Definition of energy demand function variables

$zsvd....rrlllttt$	activity of end-use technology $zsvd$ in load region l and period t,
ϵ_{zsvd}	efficiency of end-use technology $zsvd$ in converting s to d,
$\beta_{zsv\delta}^{d}$	efficiency of end-use technology $zsvd$ in producing by-product d from s (δ is the main output of the technology),
D_{drlt}	annual demand for d in load region l and period t

include front-end (from uranium import to nuclear fuel loading to the reactor) and back-end (spent fuel cooling and interim storage) activities (Equation 2.8).

$$\begin{aligned}\sum_{sv} \epsilon_{zsve} \times zsve....rrllltttt + \sum_{sv} \beta^{e}_{zsv\kappa} \times zsv\kappa....rrllltttt - \\ \sum_{zvd} zevd....rrllltttt - \sum_{zkvd} \beta^{e}_{z\kappa vd} \times z\kappa vd....rrllltttt \geq 0\end{aligned} \tag{2.8}$$

Table 2.7: Definition of energy balance function variables

$zsve....rrllltttt$	activity of the technology producing energy form e in load region l and period t,
ϵ_{zsve}	efficiency of technology $zsve$ in producing s,
$zevd....rrllltttt$	activity of the technology $zevd$ consuming energy form e in load region r and period t,
$\beta^{e}_{zsv\kappa}$	production of fuel e relative to the main output κ by technology $zsv\kappa$,
$\beta^{e}_{z\kappa vd}$	consumption of fuel e relative to the main output d by technology $z\kappa vd$

Capacities of energy conversion technologies with their output defined by load regions require investments in order to provide the availability of installed capacity to supply both base-load and also peak load demands (Equation 2.9). In case installed capacity is not capable of supplying part of the peak load there is technology for electricity import with high variable cost of 2000 US\$2005/kWyr. Technology without load region is defined as oil refineries converting crude oil to oil products whereas technology with monthly load is gas pipelines transporting natural gas (mainly Russia) for final natural gas demand (Equation 2.10).

$$\begin{aligned}\epsilon_{zsvd} \times zsvd....rrllltttt - \sum_{\tau=t-\tau_{zsvd}}^{t} \Delta(\tau-1)\,\pi_{zsvd}\,\Delta l\,f_i\,f_p \times yzsvd...rr...\tau \leq \\ hc^{t}_{zsvd} \times \Delta l \times \pi_{zsvd}\end{aligned} \tag{2.9}$$

$$\begin{aligned}\epsilon_{zsvd} \times zsvd....rr...ttt - \sum_{\tau=t-\tau_{zsvd}}^{t} \Delta(\tau-1)\,\pi_{zsvd}\,f_i\,f_p \times yzsvd...rr...\tau \leq \\ hc^{t}_{zsvd} \times \pi_{zsvd}\end{aligned} \tag{2.10}$$

Table 2.8: Definition of energy capacity function variables

$zsvd....rrllltttt$	activity of conversion technology $zsvd$ in load region l and period t,
$yzsvd...rr...ttt$	capacity variable of conversion technology $zsvd$,
ϵ_{zsvd}	efficiency of technology $zsvd$ in converting the main energy input s into the main energy output d,
π_{svd}	plant factor of technology $zsvd$,
$\Delta\tau$	length of period $\Delta\tau$ in years,
τ_{zsvd}	plant life of technology $zsvd$ in periods,
hc^{t}_{zsvd}	historical capacity of technology $zsvd$ still in operation in the first year of period t,
f_i	unit size for integer variable and 1 for non-integer,
f_p	adjustment factor if the end of the plant life does not coincide with the end of a period,
Δl	length of the load region l per length of period t

Renewable energy sources are defined in energy balance equations with upper constraints on their annual activities. Meanwhile electricity generated from hydro-power is defined using river run-off with monthly load regions and storage for dam type hydro-power generation (Equation 2.13). In the model the initial river run-off first feeds ROR type hydro-power (Equation 2.12) followed by storage in dam with additional input from run-off and electricity generation from reservoir type hydro-power (Equation 2.11).

$$I1riv....rrllltttt + W1riv....rrllltttt = 1riv....rrllltttt \tag{2.11}$$

$$I1riv....rrllltttt - z.vd....rrllltttt = 1riv....rrllltttt \tag{2.12}$$

$$\begin{aligned} &\Delta t \times I1riv - \Delta t \times z.vd....rrllltttt - \Delta t \times V1sno....llltttt + \\ &X1sto....lll^{l}ttt^{l} = X1sto....llltttt \end{aligned} \tag{2.13}$$

The energy supply system utilizes the energy resources available during the modeling horizon based on both cost and resource optimization (Equation 2.14). The energy

Table 2.9: Definition of river balance function variables

$I1riv....rrllltttt$	Inflow from $1riv$ in load region l and period t,
$W1riv....rrllltttt$	Water withdrawn from $1riv$ for storage in load region l and period t,
$z.vd....rrllltttt$	Water withdrawn from $1riv$ for producing d using technology v in load region l and period t,
$1riv....rrllltttt$	Inflow to $1riv$ in load region l and period t

Table 2.10: Definition of hydro storage function variables

$V1sno....llltttt$	Water withdrawn from $X1sto$ for other purposes in period l and period t,
$X1sto....lll^{l}ttt^{l}$	Water transferred to $X1sto$ from previous load region l^{l} and period t^{l},
$X1sto....llltttt$	Water stored in $X1sto$ during load region l and period t

content of resources hard-coal and lignite are defined in the model as available for Turkey during the modeling horizon as oil and natural gas production are negligible compared to their final energy demand.

$$\sum_{ttt}\sum_{g} rzfg.......ttt \leq rzfg.... \tag{2.14}$$

Table 2.11: Definition of resource function variables

$rzfg.......ttt$	annual extraction of resource f, cost category (grade) g in period ttt,
$rzfg....$	total available amount of resource f and grade g

2.3 Socioeconomic and technological data

The socioeconomic projections for Turkey are taken from OECD data hosted by IIASA for SSPs [153] and the techno-economic results of IAM studies evaluating the costs of carbon emission reduction represented by RCPs. The dynamic linear optimization model MESSAGE is used for modeling of energy supply system development from 2015 to 2050 with reference year 2014 based on the socio-economic and techno-economic assumptions for Baseline and climate mitigation scenarios. Turkey's historical data for population and GDP with future projections for SSPs are selected from OECD study provided in SSP database [83].

The model assumes a central planner with long-term horizon making investment decisions to minimize total energy system cost under user defined constraints. As this assumption is far from reality as many players make decisions based on short term horizons, we define temporal scales to baseline scenarios for SSPs. SSP1 with low energy demand due to major paradigm change represents low baseline, SSP3 with high energy demand represents high baseline and SSP2 represents BAU scenarios.

Emissions of atmospheric pollutants are internalized by integrating FGD for SO_2 and SCD for NO_x emissions to power plants and applying penalty costs with related data on damage [96]. The emission factors for SO_2 (Table 2.12) and NO_x (Table 2.13) from power plants are taken from Masanet et al. study as listed below[113].

Table 2.12: SO_2 emission factors from electricity generation in kton/MWyr

Technology	Emission factor
Coal_Dom_PP	0.035
Coal_Dom_PP[with_filter]	0.0035
Coal_Imp_PP	0.035
Coal_Imp_PP[with_filter]	0.0035
Oil_PP	0.043

Table 2.13: NO_x emission factors from electricity generation in kton/MWyr

Technology	Emission factor
Coal_Dom_PP	0.035
Coal_Dom_PP[with_filter]	0.0175
Coal_Imp_PP	0.035
Coal_Imp_PP[with_filter]	0.0175
Gas_PP	0.017
Oil_PP	0.021

Fricko et al. study uses the IAM framework developed by IIASA to assess the market implementation of the SSP2 scenario [49]. The IIASA framework consists of five different models complementing each other in the fields of energy, land use, air pollution, macro-economy and climate systems. The results of SSP2 take a central position between SSP1 and SSP3 considering climate change mitigation and adaptation challenges. SSP narratives describe the socio-economic pathways related to the transformation of the energy sector by the end of the 21st century (Table 2.14). The study concludes that SSP2 marker scenario reflects an extension of historical experience projecting global warming to 4°C by 2100. However there are also options to limit global warming below 2°C based on climate policy implementations including vulnerability, health and exposure aspects.

Table 2.14: Transformation of the energy sector in annual rate of change (%/yr)

Sector	SSP1	SSP2	SSP3
Energy demand intensity	-2.45	-2.00	-0.90
Transport electricification	0.62	0.45	0.11
Residential electrification	4.00	3.00	2.00
Feedstock reduction	-0.59	-0.64	-0.51

Conversion efficiencies of technologies are elaborated based on IIASA study and also considering national circumstances (Table 2.15) [81]. Unit capacities are defined for electricity generation technologies except solar and wind power plants which can be utilized at small scales [109]. The installed capacities are included in the model for oil refineries (Table 2.17), electricity transmission grids and bio-diesel production and the remaining final energy demand is calculated by conversion of primary and secondary energy sources with activity coefficients (Table 2.16). Conversion efficiency for electricity transmission and losses include losses and theft which amounts to 20% of secondary electricity generated. Process heat is supplied from CHP plant with back-pressure units using natural gas as fuel and heat extracted from coke production.

Uranium costs are taken from Optimistic Uranium Crustal models for SSPs and front-end costs from IAEA database with per kg uranium costs for extraction and conversion, per kg SWU for enrichment and per kg enriched uranium for fuel fabrication (Table 2.18). Uranium is imported as yellow cake followed by enrichment to UF_6 gas for enrichment. Uranium enrichment services are assumed to be supplied from

Table 2.15: Technology variables for power plant technologies

	Main input	Efficiency	Load factor	Lifetime (yr)	Unit capacity (MW)
Bio_PP	Biomass/PRIMARY	0.35	0.30	40	3
Coal_Dom_PP	Coal_Dom/PRIMARY	0.40	0.85	40	160
Coal_Imp_PP	Coal_Imp/PRIMARY	0.47	0.85	40	320
Gas_PP	Gas/PRIMARY	0.52	0.85	30	600
Geo_PP	Geothermal/PRIMARY	0.35	0.30	40	1
Hydro_PP_Res		1.00	0.30	60	100
Hydro_PP_ROR		1.00	0.30	60	20
Oil_PP	Oil/PRIMARY	0.34	0.85	30	100
Solar_PP		1.00	0.30	25	
Wind_PP		1.00	0.30	25	

Table 2.16: Technology variables for energy conversion technologies

Technology	Main input	Main output	Efficiency	Lifetime (yr)
Bio_TD	Biomass/PRIMARY	Biomass/FINAL	1.00	
Coal_Dom_F	Coal_Dom/PRIMARY	Coal/FINAL	1.00	
Coke_Prod	Coal_Imp/PRIMARY	Coke/FINAL	0.70	
Biodiesel	Biomass/PRIMARY	Diesel/FINAL	0.49	60
Diesel_Imp		Diesel/FINAL	1.00	
Elec_S_F	Electricity/SECONDARY	Electricity/FINAL	0.82	50
Feedstock_Imp		Feedstock/FINAL	1.00	
Fuel_Oil_Imp		Fuel_oil/FINAL	1.00	
Gas_TD	Gas/PRIMARY	Gas/FINAL	1.00	
Gasoline_Imp		Gasoline_Imp	1.00	
Kerosene_Imp		Kerosene/FINAL	1.00	
LPG_Imp		LPG/FINAL	1.00	
Oil_Ref	Oil/PRIMARY	Oil/DUMMY	1.00	60
Petrocoke_Imp		Petrocoke/FINAL	1.00	
Geo_heat	Geothermal/PRIMARY	Residential_heat/FINAL	1.00	
Solar_heat	Solar/PRIMARY	Residential_heat/FINAL	1.00	

Table 2.17: Oil product production shares of oil refineries

Oil product	Share
Diesel/FINAL	0.29
Gasoline/FINAL	0.17
Kerosene/FINAL	0.17
Feedstock/FINAL	0.14
Fuel_oil/FINAL	0.12
Petrocoke/FINAL	0.05
LPG/FINAL	0.05

abroad using SWU as secondary input required for work input. Enriched uranium is used for nuclear fuel production for loading the core of nuclear power plants for electricity generation. Variable costs for nuclear fuel cycle are taken from IAEA study [77] for advanced PWR per kg uranium fed to the process. The fuel costs for transfer from resources to primary energy sources are taken as their variable costs.

Table 2.18: Technology variables for nuclear fuel cycle

Technology	Units	SSP1	SSP2	SSP3	Upper capacity (tHM)
Uranium_imp	US$/kgU	100.00	125.00	150.00	
Conversion	US$/kgU	8.00	8.00	8.00	
Enrichment	US$/SWU	82.83	82.83	82.83	
LWR_fuel_production	US$/kgHM	275.00	275.00	275.00	
LWR_cooling_storage	US$/kgHM/yr	5.00	5.00	5.00	1000
LWR_interim_storage	US$/kgHM/yr	4.00	4.00	4.00	10000

The load factors of technologies are normalized using General Energy Balance Sheets of Turkey for reference year of 2014 [121]. Although in general load factors of base load technologies are on average 85% and of renewable energy on average 30%, the availability of domestic coal power plants which require refurbishment are reduced according to national accounts. The prices of fossil fuel extraction and import are used from IAM studies of SSPs depending on their demand and availability of resources (Table 2.19).

Table 2.19: Costs of primary energy sources in US$/kWyr

Primary energy	SSP1	SSP2	SSP3
Coal	47.30	63.07	94.61
Oil	173.45	173.45	173.45
Gas	173.45	173.45	157.68

The construction period of nuclear power plant is longer than other conventional technologies considering the planning period for site selection and licensing [111]. The construction period of other conversion technologies are below 5 years. The operation lifetime of NPPs have extended to 60 years with advanced designs whereas other conventional technologies are on average 40 years with renewable energy further below 30 years.

Although renewable energy sources are abundant by definition, their utilization depends on both socio-economic and environmental factors (Table 2.20). Most of the large hydro capacity of Turkey is already utilized leaving room for investments to ROR and mini hydropower. Although solar energy is available by two orders of magnitude more than hydropower, its mass utilization depends on techno-economic factors. The capacity potential for wind, geothermal and biomass represents the economically feasible portion [78].

Table 2.20: Feasible potentials of primary renewable energy sources

Primary energy	Main output	2014 activity (MWyr)	Maximum activity (MWyr)
Solar	Solar/PRIMARY	1069	8208000
Wind	Wind/PRIMARY	975	48000
Geothermal	Geothermal/PRIMARY	4686	31500
Biomass	Biomass/PRIMARY	1881	13433

Most of the coal resources are categorized under brown coal and lignite which is grouped as lignite in the model (Table 2.21). Hard coal reserves are limited therefore the deficiency is supplied by imported coal with high calorific value. Although there is no uranium mining activity in Turkey, there has been exploration and mine development activities since 1970s with potential sites for mining depending on their feasibility under low uranium prices [128].

Table 2.21: Domestic coal reserves in MWyr

Primary energy	Resources
Lignite	2465753
Hardcoal	440925

2.4 Robustness of electricity supply system

The supply of electricity should meet the requirements for demand load fluctuations and ancillary services for robustness of the grid to supply the required voltage and frequency during all times. This robustness is defined by the adequacy, security and reliability of the electricity supply system from secondary electricity generation until final demand. The flexibility requirement in MESSAGE model is defined as a linear constraint with fossil power plants increasing and renewable power plants decreasing the contribution to supply final electricity demand load fluctuations (Equation 2.15) [168].

$$Parameter \cdot Electricity\ generation \geq 0 \tag{2.15}$$

Although nuclear energy generation could suit demands for load following, this is not the preferred solution due to buildup of fission products inside core and mechanical stress imposed on reactor containment vessel [87]. The capacity of technologies for flexibility to supply peak demand is taken from Sullivan et al. [168] assessing the reliability of electricity sector using peak load, resource availability and system dispatch data in the U.S. using MESSAGE. The results show that flexibility requirements (Table 2.22) for load following increases marginal costs of renewable energy technologies and reduces their investments.

The adequacy of the electricity supply system requires available resources to provide a continuous supply in normal operating conditions. Both energy resources and electricity generation installed capacity should be available to cover the demand. Security

Table 2.22: Flexibility parameters for the electricity grid

Electricity generation	Parameter
Total annual electricity	-0.1
Wind	-0.08
Solar PV	-0.05
Geothermal	0
Nuclear	0
Coal	0.15
Biopower	0.3
Combined cycle gas	0.5
Hydropower	0.5
Oil steam turbine	1
Gas combustion turbine	1

of electricity supply deals with unexpected failures and contingencies. The intermittency of renewable energy sources such as wind and solar power create problems for supplying unexpected fluctuations in demand. Also the electricity grid should have available capacity to compensate any transmission capacity which is not available for usage. This also requires the reliability of the electricity transmission system to balance the demand with supply at all times.

Electricity which is non-storable should be generated based on the fluctuations in final demand. Power generators are requested to ramp-up or ramp-down production by the transmission operator in order to supply the demand load. Natural gas demand for final energy used for residential heat increases during winter time and decreases during summer time. Storage of natural gas in saline aquifers is planned in Turkey to protect the market from price volatility and supply the peak demand in case of harsh winters [8]. The filling of hydropower reserves and run-off for river type power plants depends on annual precipitation and evaporation loads with monthly average precipitation rates between 1970 and 2017 are taken as proxy [8].

Final electricity demand requires available capacity to supply peak hours where consumption is more than average. NPPs operated in countries with large penetration of renewable energy generation contribute to primary and secondary reserves for stabilization of generation to supply load changes and also the frequency of electricity supplied in the grid [27]. The capacity of technologies to ramp up or down electricity production depends on their physical properties for combustion energy and environmental properties for renewable energy. Electricity transmission operator should guarantee the stability of load and frequency in order to balance the supply and demand of electricity in all load regions. This is accomplished by hot reserves with available capacity to ramp-up or ramp-down and cold reserves with additional capacity which can be ordered to take load on peak demand. Fossil fueled power plants with large turbine-generators contribute positive to flexibility whereas intermittent renewable sources contribute negatively. Hydro-power with reservoir provides storage capacity supporting the flexibility of the grid. Nuclear has low rates of ramp-up and ramp-down due to neutronic and thermal properties and requires fossil reserves in case of power outages (Table 2.23).

Table 2.23: Power change requirements for power plants (MW/hr)

Power plant	Ramp up	Ramp down
Gas_PP	120	120
Gas_PP[with_CHP]	60	60
Nuclear_PP	100	100
Coal_Dom_PP	16	16
Coal_Imp_PP	32	32

The transition from centralized electricity grid system to more distributed generation requires both technological and also institutional solutions which can create challenges for developing countries [107]. Distributed electricity generation provides advantages for local and regional electrification and also reducing investment requirements for grid infrastructure. However the energy system requires additional power generation sources in case of power outages requiring low carbon transition mechanisms as the most available sources are diesel generation in these situations.

2.5 Earth system feed-backs

The relationship between the climate and the earth system is bi-directional whereas the feed-backs from earth system due to the radiative forcings could either stabilize or increase the impact on climate change. Land and oceans are potential sources and sinks of carbon in the atmosphere whereas climate change could have impact on these capacities [104]. SSPs have varying implications on land use change which requires further research not only by IAM researchers but also by ecological and climate scientists [147]. These stresses could generate climate extremes with impacts not only on the physical interactions of the earth system but also on social services requiring focus on these issues [164].

The IAM studies include linkages of energy sector with land and water use as carbon cycle includes bi-directional interactions between atmosphere, lithosphere and hydrospere. Atmospheric carbon concentration is effected by sources and sinks with different residence times in the organic and inorganic carbon reservoirs [117]. The rate of increase in surface temperature depends both on the initial conditions and historic trajectories which determine the climate sensitivity used for climate models. The SSPs are classified based on the challenges for achieving climate change mitigation and adaptation.

The metrics used for the radiative forcing of GHGs has effect on the results of IAM studies for quantification of the socio-economic and climate scenarios [66]. There are different GHGs such as CH_4 and N_2O originating from energy upstream activities contributing to radiative forcing with temporally different global warming potentials (Table 2.24). The global warming potential of these GHGs are compared to the impact of radiative forcing generated by CO_2 with temporal scale of 20 and 100 years. Selection of the energy system modeling time horizon with respect to the lifetime used for GWP metric has effect on the costs of GHG emission reduction for all models.

The carbon cycle in the earth system is still dominated by natural processes of sources and sinks which are projected to change in the temporal scale of energy supply system models used for assessing climate change mitigation policies. The impact of

Table 2.24: Global warming potentials for temporal scales of 20 and 100 years

Metrics	Target	CH_4 (CO_2=1)	N_2O (CO_2=1)
GWP 100 (AR4)	2.8 W/m2 or 3.7 W/m2	25	298
GWP 20 (AR4)		72	289

GHG emissions have long term effects on radiative forcing where the results of current emission trends will be effective in the second half of the 21st century [90]. The potential role of negative emission technologies after 2050 would increase the remaining carbon budget in the atmosphere requiring further assessment for both negative feedback from reduced reliance on upstream activities and positive feedback from rebound effect [61].

CHAPTER 3

ANALYSIS OF RESULTS

3.1 Modeling results

The marginal costs of generating electricity provide price signals for selecting the technology for supplying increasing electricity demand. The dynamic linear cost optimization algorithm of the model compares these marginal costs with the lifetime costs of energy technologies including their capital and operation costs discounted during their operation lifetime. This selection is also affected by other user defined constraints such as electricity grid flexibility requirement and resource availability. The results at the end of the modeling period are affected by end-of-horizon effect. The capital costs are for all operation lifetime whereas investments at the end of the modeling period have less operation lifetime which is reflected by reducing their capital costs. Therefore investment results at the end of the modeling period should be evaluated with caution.

High capital cost of nuclear energy requires financing strategies to be utilized in order to minimize the financial risk [172]. Construction scheduling is also essential in order to prevent cost escalations of major projects [22]. Few new-build nuclear countries, such as Saudi Arabia or UAE, can finance nuclear projects relying on their domestic financing resources. New projects adopt project financing through establishment of SPVs for non-recourse of financial responsibility to the project sponsors. However there are constraints from licensing as nuclear operators have exclusive liability for safety and organizations in new-build countries generally lack proven experience to cover this responsibility [161].

3.1.1 Energy system costs

Energy system costs are discounted to the initial year 2015 using social discount rate of 5.06% [64]. As a result the technologies with high initial capital costs are delayed towards the end of the modeling horizon as they will have reduced costs for the current generation. Technologies with long operating lifetimes such as NPPs are also affected by the end-of-horizon effect where their capital costs are reduced in accordance to the remaining period until the end of the modeling horizon (Equation 3.1).

$$C_t^r = C_t \times \frac{\sum_{k=1}^{\tau_p-\nu} \prod_{\tau=t}^{t+k-1} \frac{1}{1+dr_\tau}}{\sum_{k=1}^{\tau_p} \prod_{\tau=t}^{t+k-1} \frac{1}{1+dr_\tau}} \tag{3.1}$$

Table 3.1: Definition of end of horizon function variables

ν	number of years technology is operation after end of modeling horizon
dr_τ	discount rate for year τ
τ_p	plant life in years
C_t	investment cost in year t
C_t^r	reduced investment considering the modeling horizon

The increase in discounted total energy system cost from baseline to RCP2.6 in SSP1 is 15% after the costs of atmospheric emissions are mitigated by investments in low carbon technologies (Figure 3.1). This increase is reduced to 6% for RCP3.4 and 2% for RCP4.5 as a result of reduced costs of CO_2 emissions. The higher increase of cost in RCP2.6 is also affected by lack of mitigation options in the energy system which can benefit from additional demand side technology innovations.

The objective function discounts the energy system costs related to the installation, operation and maintenance together with user defined external costs of energy conversion technologies (Table 3.2). The share of externality costs in Baseline scenario is related to the costs of penalty for SO_2 and NO_x emissions which can be reduced by using emission filters in coal power plants. The operation of these filters reduces SO_2 emissions by 90% and NO_x emissions by 50% reducing the penalty costs.

Costs of CO_2 emissions are included for RCPs which increases the share of costs

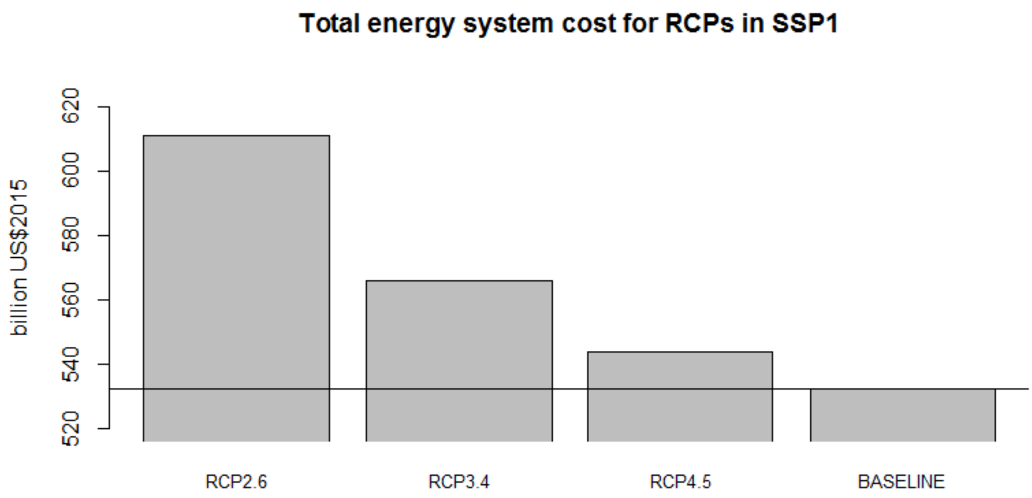

Figure 3.1: Energy system costs for RCPs in SSP1 compared to baseline

related to externalities from 2.5% of total cost for Baseline to 9.6% in RCP2.6. The increasing cost of externalities in RCP scenarios provide an opportunity for using these costs for investing in low carbon technologies. This results in transfer of revenues from fossil fueled power plants to low carbon technologies reducing the total energy system cost.

Table 3.2: Total energy system costs (billion US$) in SSP1

Code	Definition	Baseline	RCP4.5	RCP3.4	RCP2.6
car1	Externality costs	33	50	81	140
ccap	Installation costs	180	183	187	201
ccur	O&M costs	1130	1130	1130	1120
	Total	1340	1360	1390	1460

The total discounted energy system cost for RCP2.6 in SSP2 increases by 33% compared to Baseline which reduces to 16% for RCP3.4, 11% for RCP4.5 and 8% for RCP6.0 (Figure 3.2). The main reason for higher increase in total energy system cost is the lower learning rate of low carbon technologies as a result of less ambition for climate mitigation compared to SSP1 narrative. There is also a potential for compensating this higher increase by usage of revenues from emission penalty costs for investing in low carbon technologies.

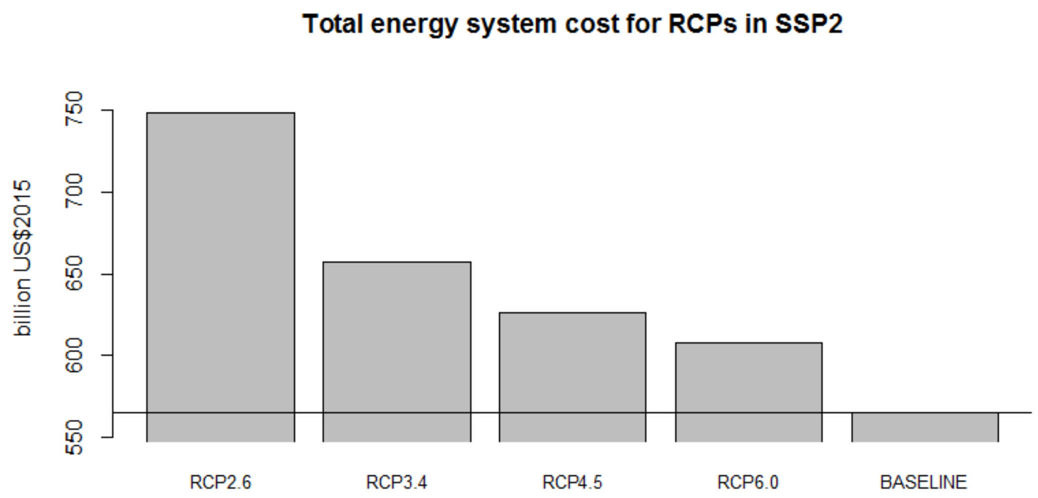

Figure 3.2: Energy system costs for RCPs in SSP2 compared to baseline

Energy system costs for SSP2 are higher compared to SSP1 as a result of reduced energy efficiency improvements and higher projections of population resulting in higher final energy demand (Table 3.3). Costs of CO_2 emission are included for RCPs which increases the share of costs related to externalities from 2.7% in Baseline to 17.5% in RCP2.6. The rapid increase of installation and externality costs for RCP2.6 requires larger requirements for financing which can be compensated by revenues from emission penalty costs.

Table 3.3: Total energy system costs (billion US$) in SSP2

Code	Definition	Baseline	RCP6.0	RCP4.5	RCP3.4	RCP2.6
car1	Externality costs	38	81	111	163	299
ccap	Installation costs	136	136	138	138	195
ccur	O&M costs	1240	1240	1240	1240	1210
	Total	1420	1460	1490	1540	1710

Total energy system cost for RCP3.4 in SSP3 increases by 43% compared to baseline due to higher prices for CO2 emissions under ambitious climate targets which is reduced to 24% for RCP4.5 and 12% for RCP6.0 (Figure 3.3). The higher increase in total energy system costs for SSP3 is based on the higher projection for population increase and lesser improvements in energy efficiency resulting in higher increase in final energy demand. The energy system requires high capital investment to supply this increasing demand which makes the achievement of mitigation targets more difficult compared to SSP2 and SSP1 scenarios.

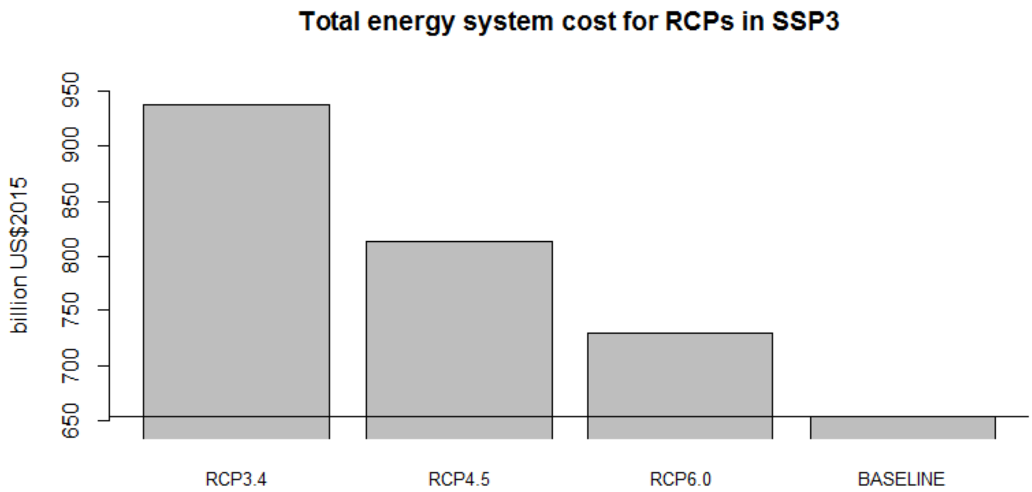

Figure 3.3: Energy system costs for RCPs in SSP3 compared to baseline

Energy system costs for SSP3 are higher similar to SSP2 as a result of reduced energy efficiency improvements and higher projections of population resulting in higher final energy demand (Figure 3.4). RCP scenarios include penalty costs for CO_2 emissions which increases the share of costs related to externalities in total energy system costs from 2.4% in Baseline to 23.3% in RCP3.4. The rapid increase of installation and externality costs for RCP3.4 requires larger requirements for financing with questions concerning the feasibility of low carbon energy investments.

Turkey is still one of the few countries which have signed but not yet ratified the Paris Agreement of the UNFCCC. However Turkey also continues to invest on low carbon energy technologies using both domestic and international financing mecha-

Table 3.4: Total energy system costs (billion US$) in SSP3

Code	Definition	Baseline	RCP6.0	RCP4.5	RCP3.4
car1	Externality costs	38	133	266	480
ccap	Installation costs	130	132	145	186
ccur	O&M costs	1420	1410	1410	1400
	Total	1590	1680	1820	2060

nisms. The revenues which can be collected from penalty costs of emissions in energy system range from 33.26 to 480.23 billion US$ depending on the penetration rate of low carbon energy technologies (Table 3.5). Transferring of these revenues towards investment for low-carbon energy sources can be considered as green investment and budget constraint for renewable energy technologies with high capital costs.

Table 3.5: Cumulative revenues from emission penalty costs (billion US$)

	RCP2.6	RCP3.4	RCP4.5	RCP6.0	Baseline
SSP1	140.28	81.49	50.35	-	33.26
SSP2	299.12	163.03	110.74	81.44	37.96
SSP3	-	480.23	266.12	132.69	38.63

The strategies for climate mitigation in many large GHG emitting countries include FITs for subsidizing renewable energy investments [156]. Taking into consideration that large increases in total energy system costs for climate mitigation would result in decrease of welfare, the modeling framework considers the usage of these revenues as FITs for solar power, geothermal and biomass power plants. These technologies are selected as they have small penetration levels to the energy system compared to other renewable technologies such as wind and hydro power.

The cumulative constraint is defined as the maximum total generation capacity of low carbon technologies with FITs. The costs of electricity generation are subsidized from cumulative revenues until this total generation capacity is reached for both RCP and Baseline scenarios in SSPs. The FIT prices are 1165 US$/kWyr for solar PV and biomass power plants whereas geothermal power plants benefit from 920 US$/kWyr [47]. The reduction of costs from electricity generation from these technologies provide a subsidy whereas the available revenue to cover these costs also provides a maximum constraint in Equation 3.2.

$$TotRev \geq Elec_{PV} * FIT_{PV} + Elec_{Bio} * FIT_{Bio} + Elec_{Geo} * FIT_{Geo} \tag{3.2}$$

Table 3.6: Definition of cumulative constraint variables

$TotRev$	Total revenue from payments for atmospheric emission penalties,
$Elec_n$	Total electricity generation from technology n,
FIT_n	Subsidy given to technology n for electricity generation

The revenues collected from atmospheric emission penalties reduce the increase in total discounted energy system cost for all scenarios. The total revenue amount depends on both electricity generated from fossil power plants and penalty costs used in the model. The increases in total discounted energy system cost for SSP1 are 8% for RCP2.6, 3% for RCP3.4 and 1% for RCP4.5 (Figure 3.4) compared to Baseline. These results for SSP1 shows that stringent climate targets require additional mitigation strategies in order to reduce the higher increase for RCP2.6.

The increase in total discounted energy system cost for SSP2 are 24% for RCP2.6, 12% for RCP3.4 and 8% for RCP4.5 and 6% for RCP6.0 compared to Baseline (Figure 3.5). Achievement of stringent climate targets for SSP2 requires large transformation of the energy supply system compared to SSP1 scenarios. The narrative of SSP2 with lower penetration of renewable technologies and lower improvement in energy efficiency results in higher increase in total discounted energy system cost.

The increase in total discounted energy system cost for SSP3 are 39% for RCP3.4, 22% for RCP4.5 and 10% for RCP6.0 compared to Baseline (Figure 3.6). The narrative of this scenario is characterized by high challenges for both climate mitigation and adaptation which makes reaching climate targets more difficult than other scenarios. Investment for low carbon energy technologies is not sufficient to reduce carbon concentration as higher population growth and lower energy efficiency improvement increases the total discounted energy system cost.

We should also assess the usage of the cumulative revenues from emission penalties

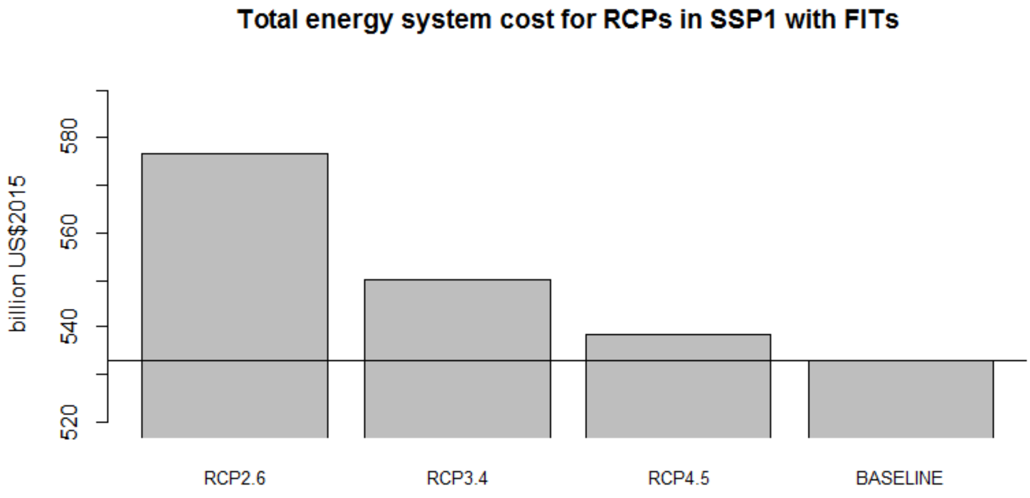

Figure 3.4: Energy system costs for RCPs with FITs in SSP1 compared to baseline

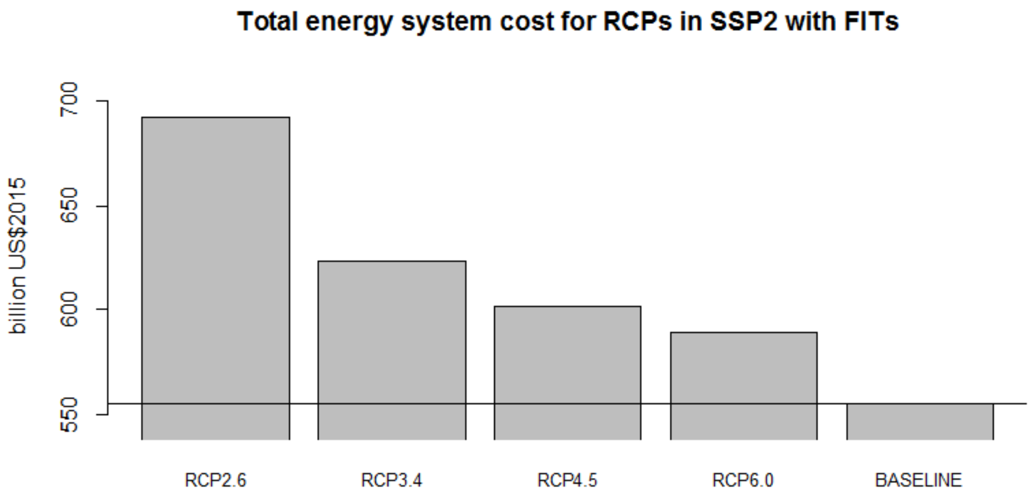

Figure 3.5: Energy system costs for RCPs with FITs in SSP2 compared to baseline

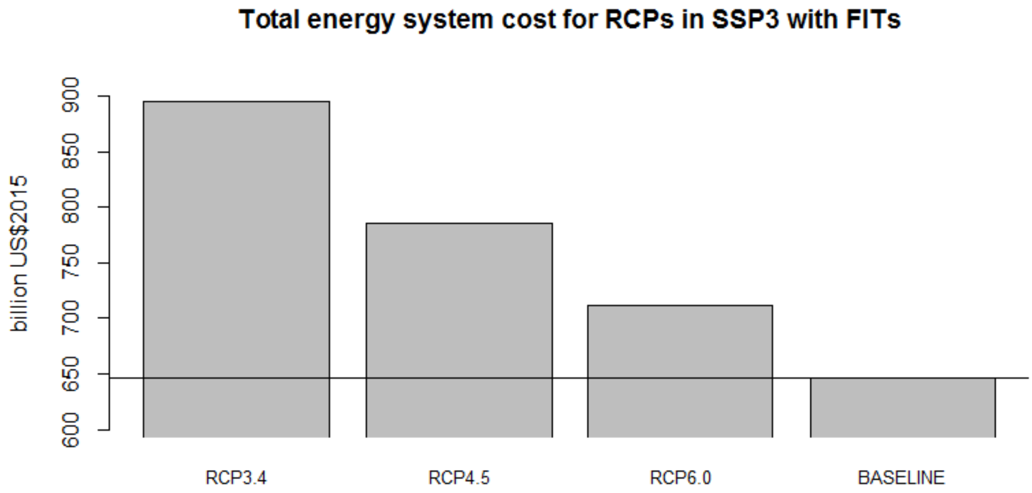

Figure 3.6: Energy system costs for RCPs with FITs in SSP3 compared to baseline

Table 3.7: Total payments used for FITs (billion US$)

	RCP2.6	RCP3.4	RCP4.5	RCP6.0	Baseline
SSP1	119.04	69.52	42.96	-	28.26
SSP2	199.38	115.96	80.41	59.04	27.97
SSP3	-	274.97	178.18	95.47	28.17

as the investments on low carbon technologies depends on marginal costs of final energy demand depending on SSP narratives. Comparing the total payments with FITs for electricity generation (Table 3.7) with cumulative revenues from emission penalties (Table 3.5) provides an opportunity on assessing the effectiveness of this climate mitigation strategy. The share of FIT payments to revenues (Table 3.8) are on the same level for all RCPs in SSP1 arguing that FITs are an effective mitigation strategy. This situation is different for SSP2 and SSP3 scenarios where the share of FIT payments to revenues are lower for the most stringent climate targets.

Table 3.8: Shares of total FIT payments in revenues from emission penalties (%)

	RCP2.6	RCP3.4	RCP4.5	RCP6.0	Baseline
Low (SSP1)	84.9	85.3	85.3	-	84.9
Medium (SSP2)	66.7	71.1	72.6	72.5	73.7
High (SSP3)	-	57.3	66.9	71.9	72.9

3.1.2 Electricity generation capacity

Electricity capacity expansion is calculated by the model based on optimization of total energy system cost subject to constraints defined based on the scenarios. The lifetime of historic capacities are included as vintages during the modeling horizon and investments to compensate the capacity deficit resulting from increasing final energy demand are assumed to be met by a central planner. Marginal costs of electricity generation during the modeling horizon determine the temporal dimension of investment decisions for low carbon technologies.

The resulting investments for electricity generation in SSP1 can be seen with rapid investment to solar and wind power plants starting from 2030 for decarbonization of the electricity sector (Figure 3.7). Investments for gas, oil and coal power plants continue from 2015 to 2045 as replacement of obsolete units and grid flexibility requirements. Investments for NPPs starts in 2035 as a complement to renewable power plants for transformation of the energy system to a low carbon future.

The capacity difference figures are calculated by substracting the total installed capacites of technologies in RCP and Baseline scenarios. Positive values show that

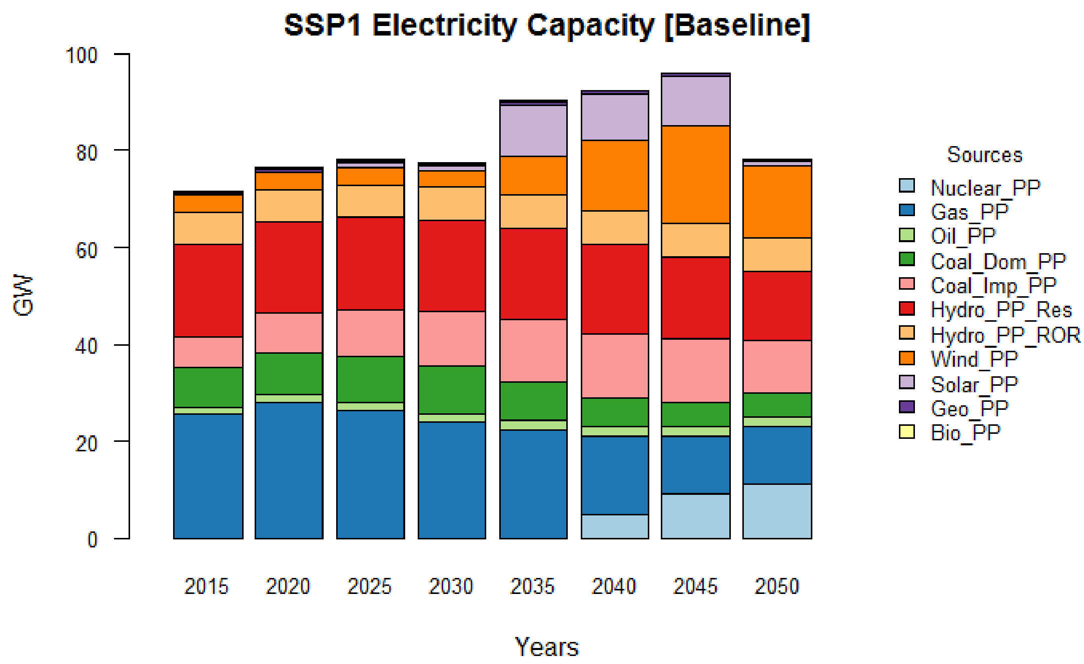

Figure 3.7: Electricity capacity expansion in SSP1 for Baseline

RCP scenario require additional investments whereas negative values show the effect of substitution as a result of CO_2 emission penalties. Investment for solar PV starts in 2025 for RCP4.5 in SSP1 as a result of increase in revenues from CO_2 emission penalties (Figure 3.8). This additional investment is substituted from investments for NPPs between 2045 and 2050.

The investment capacity for solar and wind power plants for RCP3.4 are higher compared to RCP4.5 and Baseline in SSP1 (Figure 3.9). This result is reasonable as there are higher revenues from CO_2 emissions compared to lesser ambitious climate mitigation targets. In addition to the higher penetration of wind and solar power plants, the substitution of nuclear power with renewable energy technologies starts in 2040.

The most stringent climate target with RCP2.6 forcing maximizes the penetration of wind and solar power plants with their total difference reaching 80 GW compared to Baseline (Figure 3.10). This increase is substituted by NPPs starting from 2040 and by gas power plants starting from 2020.

The higher increase in final energy demand for Baseline scenario in SSP2 compared to

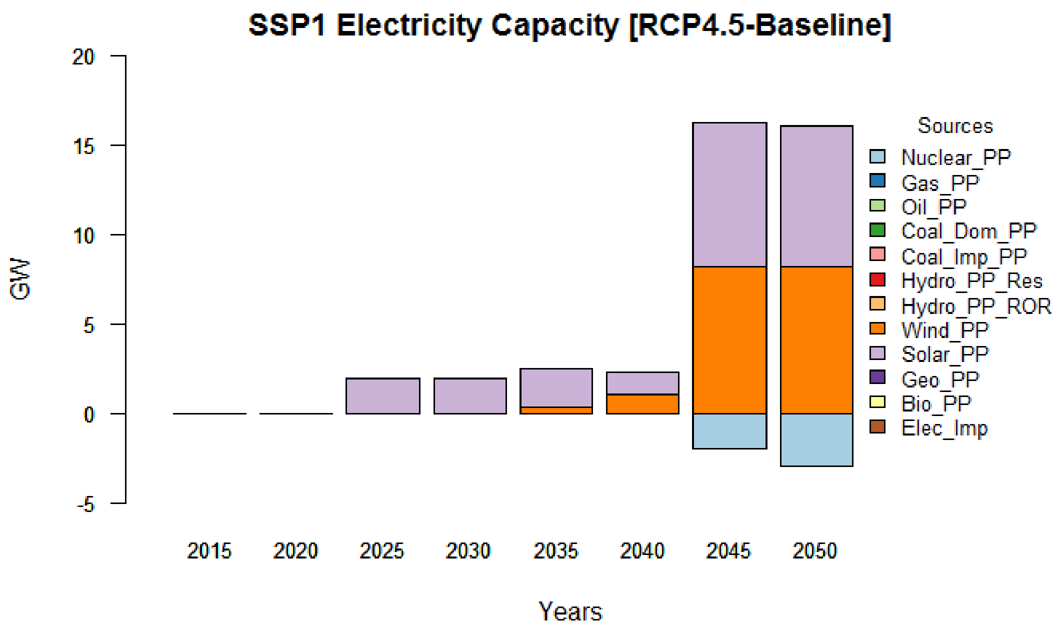

Figure 3.8: Electricity capacity difference in SSP1 for RCP4.5

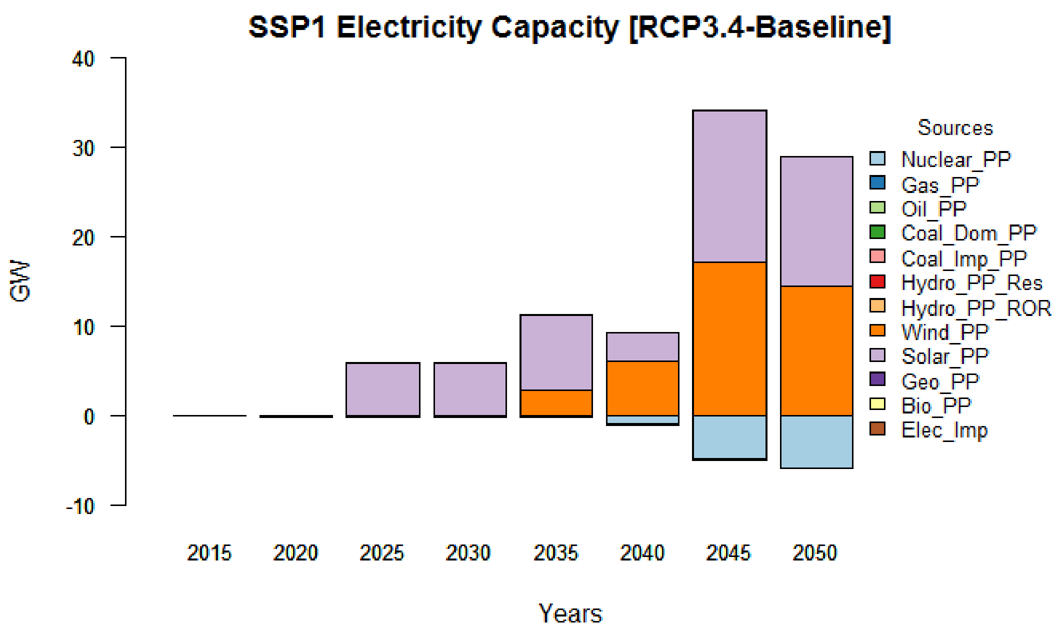

Figure 3.9: Electricity capacity difference in SSP1 for RCP3.4

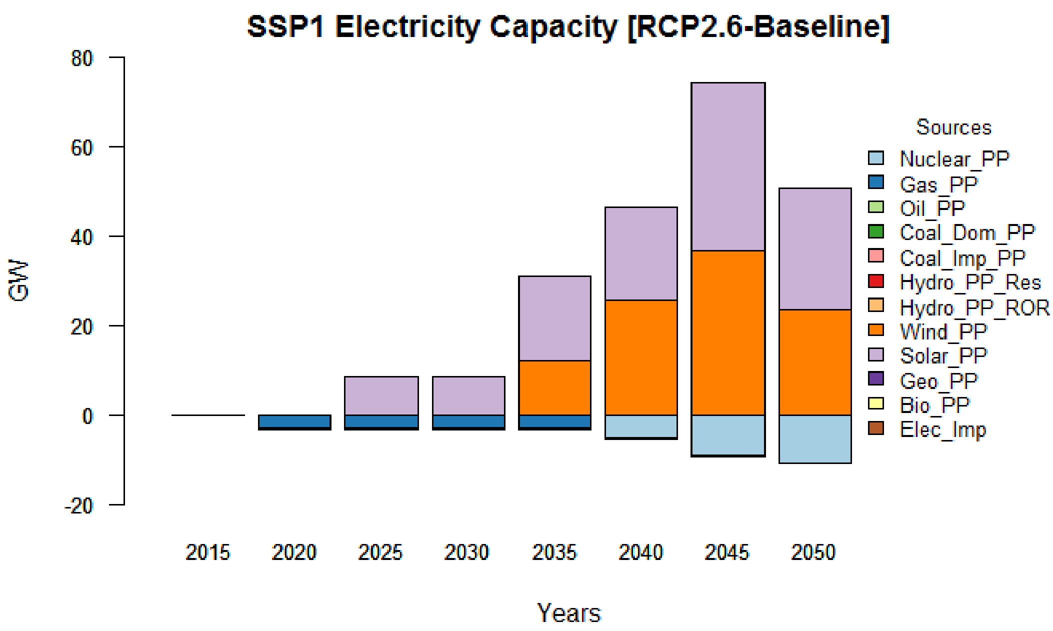

Figure 3.10: Electricity capacity difference in SSP1 for RCP2.6

SSP1 causes investment in both low carbon and fossil fuel technologies in electricity generation (Figure 3.11). Investment for renewable energy portfolio is expanded by additional capacity expansion in ROR hydro power and biomass power plants. NPP investment starts in 2030 and increases up to 13 GW by the end of the modeling horizon. These results show that the requirement for climate mitigation has lower importance compared to SSP1 and higher increase in final energy demand is partially met by NPP investments.

Implementing the CO_2 emission penalty costs for RCP6.0 in SSP2 forces the substitution of a small part of NPPs with solar and wind power starting from 2030 (Figure 3.12. Additional investments for solar power plants also start as early as 2020 for transition to low carbon energy supply system. This transition is similar for RCP4.5 in SSP2 requiring larger additional installed capacity for solar and wind power (Figure 3.13).

The most stringent climate targets in SSP2 requires additional substitution of gas power plants in order to increase wind and solar power plant investments. Additional

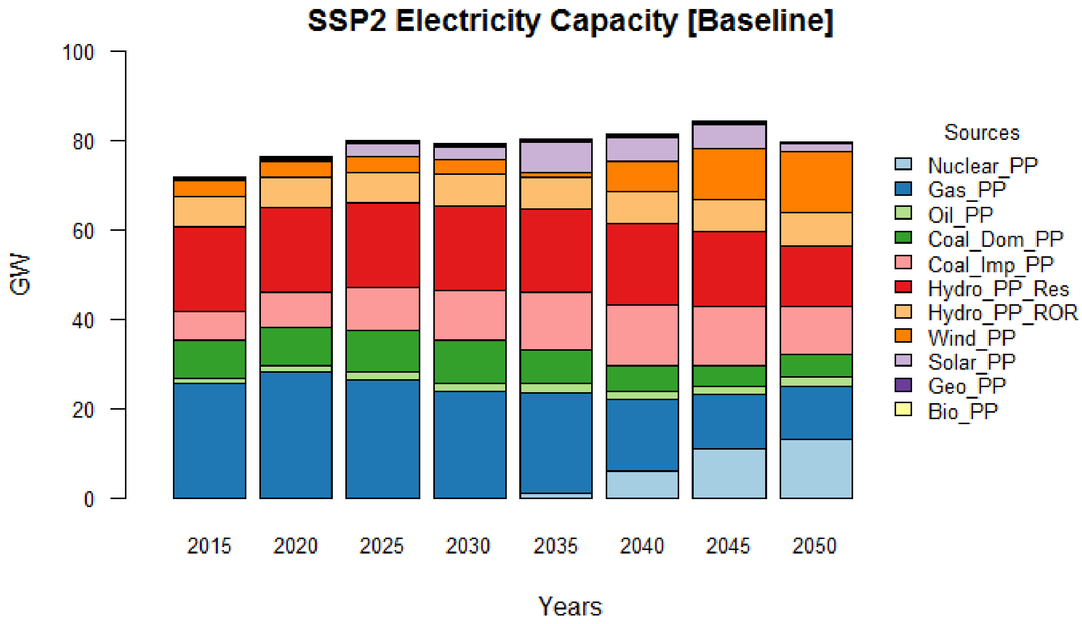

Figure 3.11: Electricity capacity expansion in SSP2 for Baseline

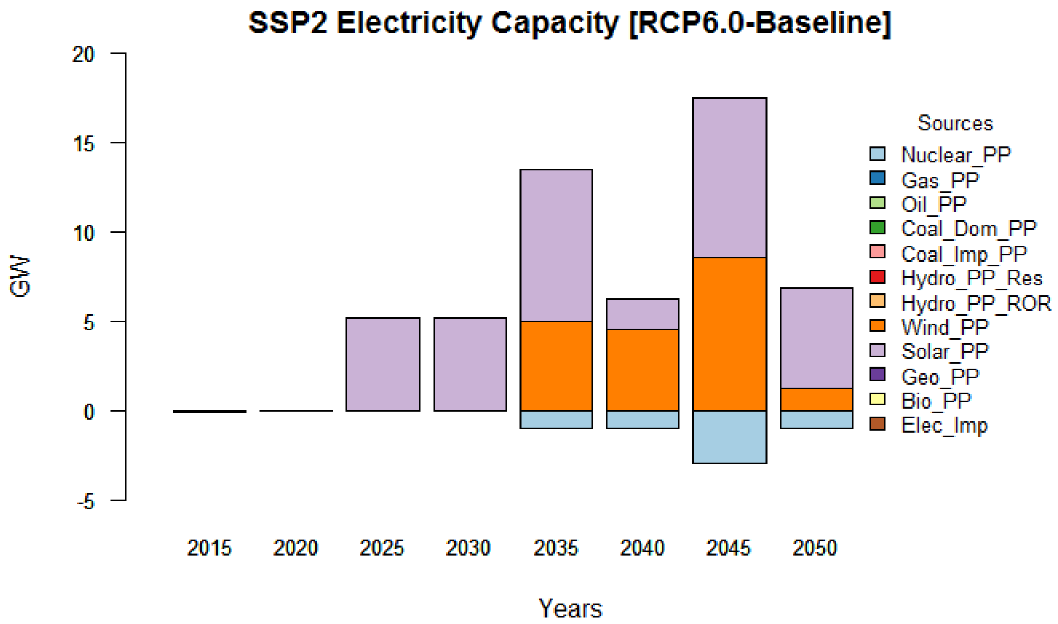

Figure 3.12: Electricity capacity difference in SSP2 for RCP6.0

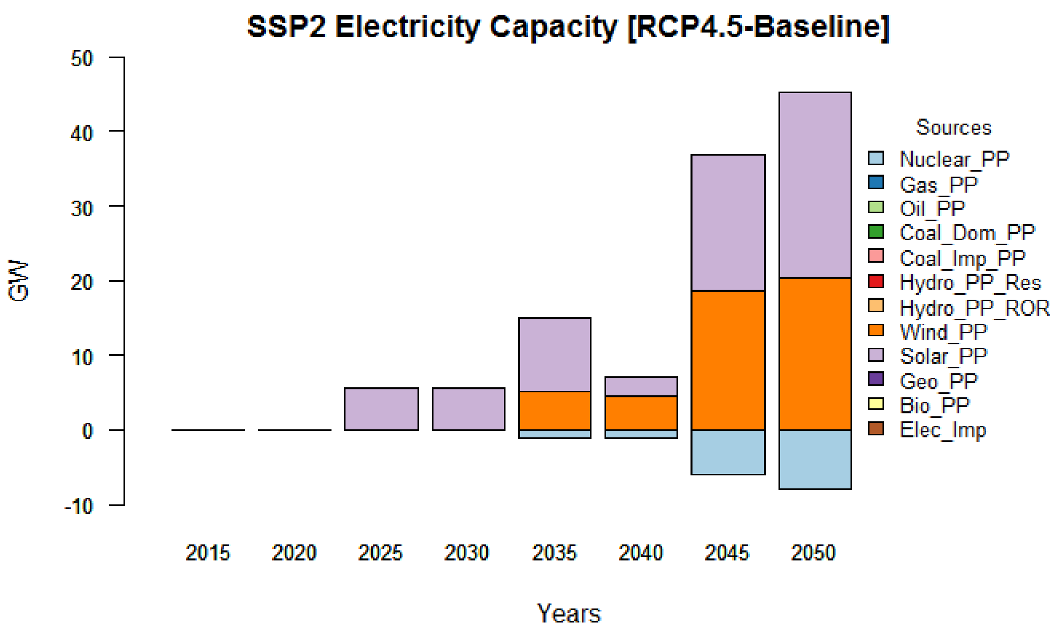

Figure 3.13: Electricity capacity difference in SSP2 for RCP4.5

renewable energy installed capacity additions by the end of the modeling horizon reaches 60 GW for RCP3.4 (Figure 3.14) and 120 GW for RCP2.6 (Figure 3.15). Although higher capacity addition in renewable energy technologies would contribute to achieving climate targets, the intermittency of these energy sources would cause concerns for flexibility of the grid system to supply peak load final electricity demand.

Electricity capacity investments for Baseline scenario in SSP3 includes both fossil and renewable energy technologies as a result of higher increase in final energy demand compared to SSP2 and SSP1 narratives (Figure 3.16). Investments for NPPs start as early as 2015 which substitutes the gas power plants competing their operation lifetimes. The end-of-horizon effect is dominant for wind and solar power plants which have investments at the end of the modeling horizon. Large hydro power plants which complete their operating lifetime are replaced by the end of the modeling horizon also as a result of this effect.

SSP3 narrative is characterized by lower energy efficiency improvements and higher population growth resulting in higher energy demand. As a result even the least am-

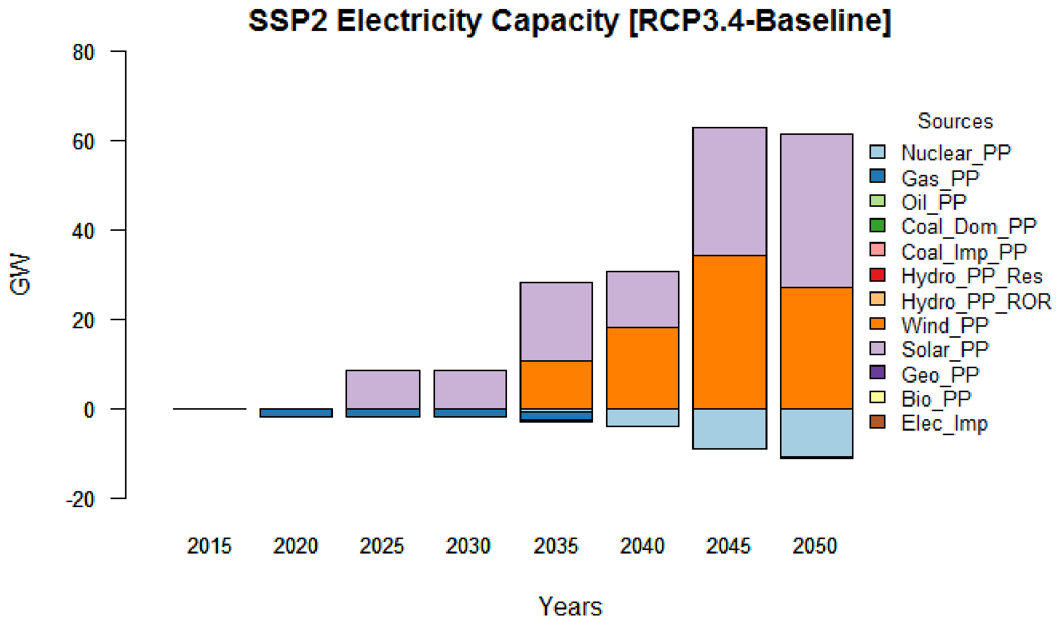

Figure 3.14: Electricity capacity difference in SSP2 for RCP3.4

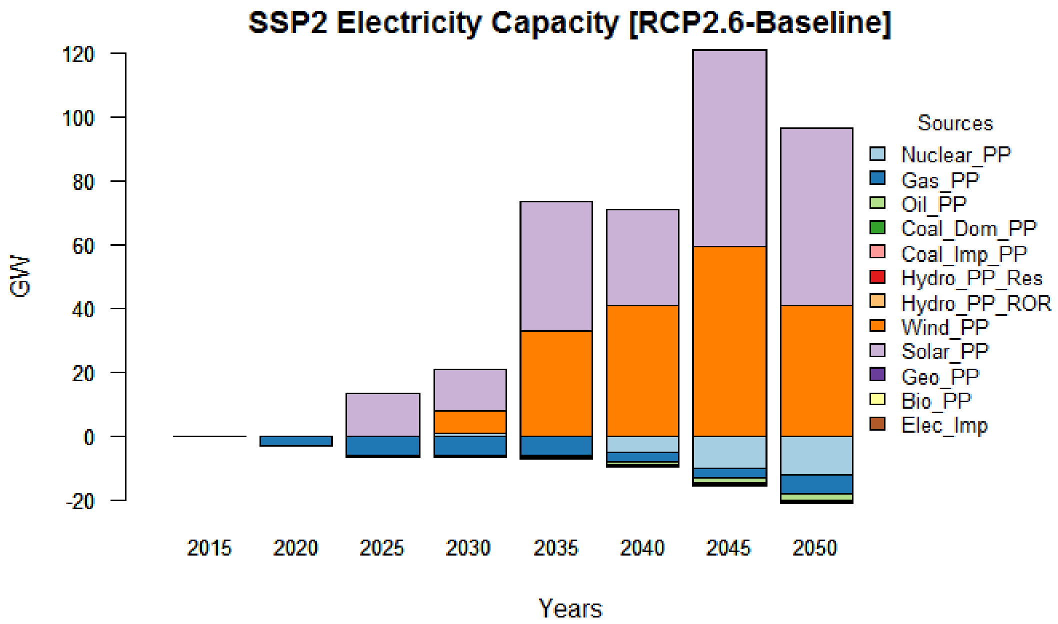

Figure 3.15: Electricity capacity difference in SSP2 for RCP2.6

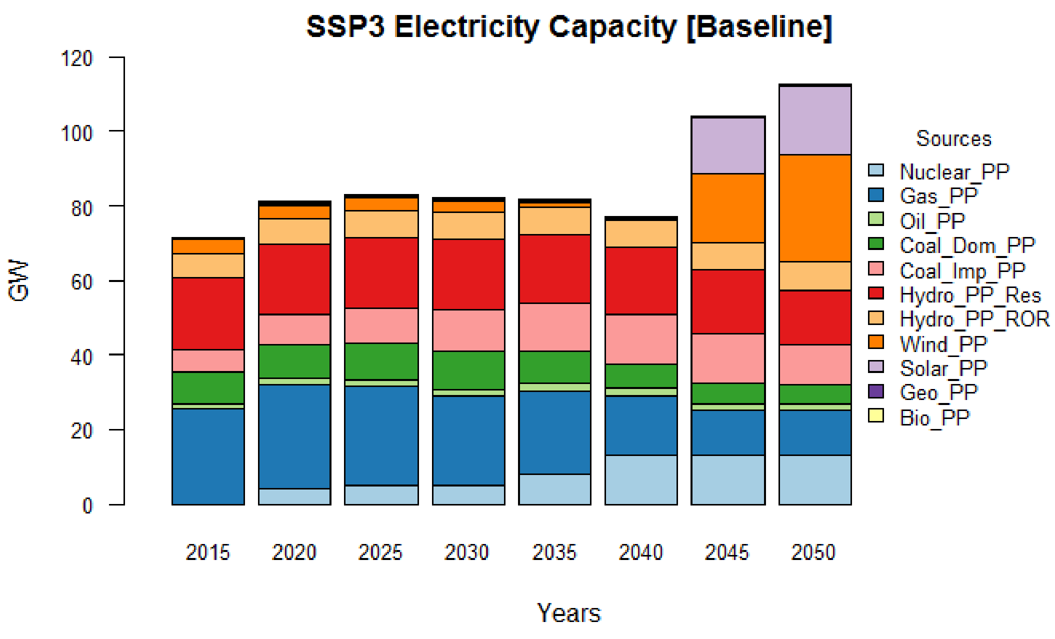

Figure 3.16: Electricity capacity expansion in SSP3 for Baseline

bitious climate target of RCP6.0 requires additional 30 GW of wind and solar power plant capacity in total by the end of the modeling horizon (Figure 3.17). The IAM results for SSP3 provide higher prices for coal as a result of increasing final energy demand and lower energy efficiency improvements [49]. As a result additional renewable energy capacity requires substitution with both NPPs and coal power plants for optimization of total discounted energy system cost. The replacement of large hydro power plants with expired operating lifetimes are substituted with wind and solar power plant investments.

Climate target for RCP4.5 in SSP3 requires additional substitution of domestic coal power plants in addition to NPPs and gas power plants (Figure 3.18). Additional wind and solar power capacity reaches 120 GW in total by the end of the modeling horizon which is four times more than for RCP6.0 in SSP3. The replacement of large hydro power plant with expired operating lifetimes are again substituted with wind and solar power plant investments as for RCP6.0.

Increasing the climate ambition further to RCP3.4 in SSP3 requires additional substi-

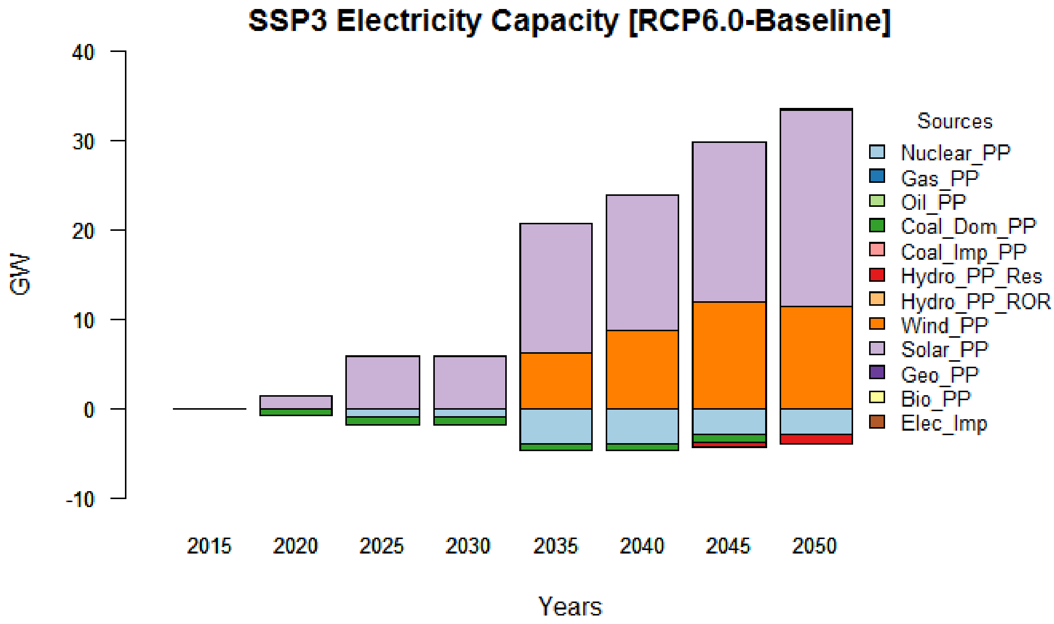

Figure 3.17: Electricity capacity difference in SSP3 for RCP6.0

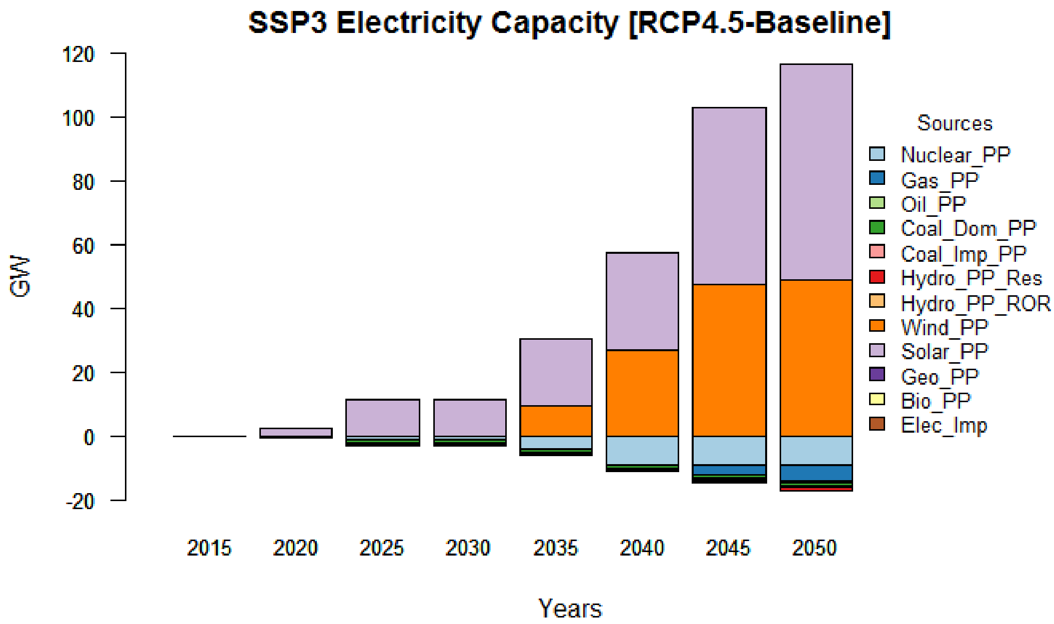

Figure 3.18: Electricity capacity difference in SSP3 for RCP4.5

tution of import coal and oil power plants in addition to domestic coal and gas power plants and NPPs (Figure 3.19). Additional wind and solar power capacity required by the end of the modeling horizon exceeds 150 GW increasing concerns to supply peak load final electricity demand due to their intermittency.

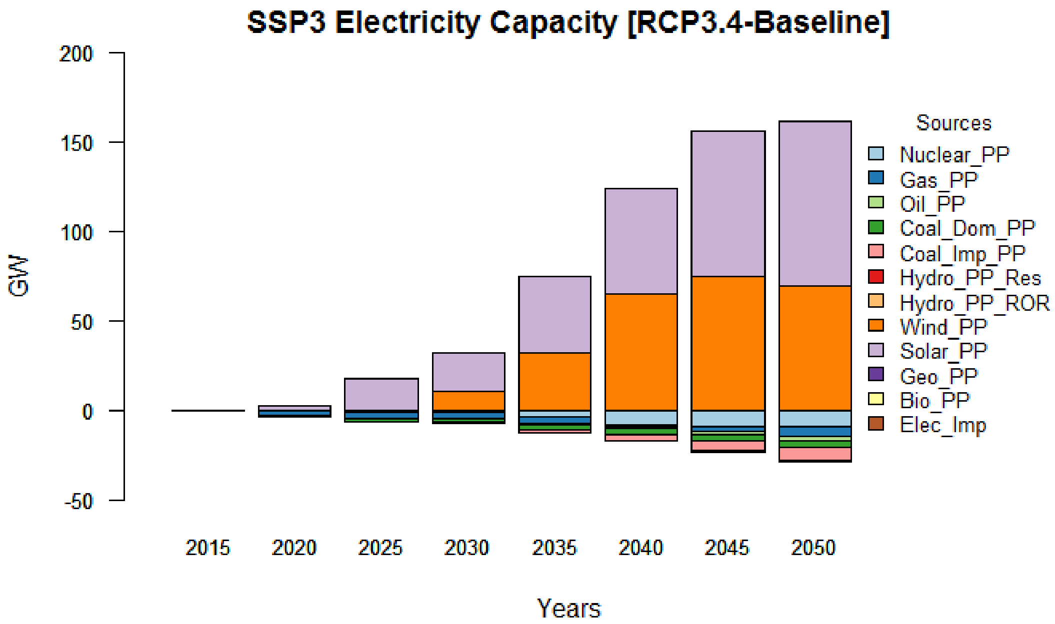

Figure 3.19: Electricity capacity difference in SSP3 for RCP3.4

The results are based on the assumption that revenues collected from atmospheric emission penalties are used for subsidizing solar, geothermal and biomass power plants through FITs. As these revenues increase together with increasing CO_2 emission prices for RCPs, part of the NPP investments are substituted with wind and solar power plants during the modeling horizon. The merit order of substitution is on the cost bases starting with the technology with highest cost being NPPs.

3.1.3 Electricity generation costs

The reference energy system in 2014 is defined in the model as initial year which requires investments for further optimizing the total discounted energy system costs during the modeling horizon. Increase in final energy demand which is defined exogenously in the model increases the marginal costs creating price signal for further capacity investment. The impact of higher CO_2 emission penalty costs can be seen in 2030 for SSP1 which is neutralized as a result of investments in low carbon technologies (Figure 3.20).

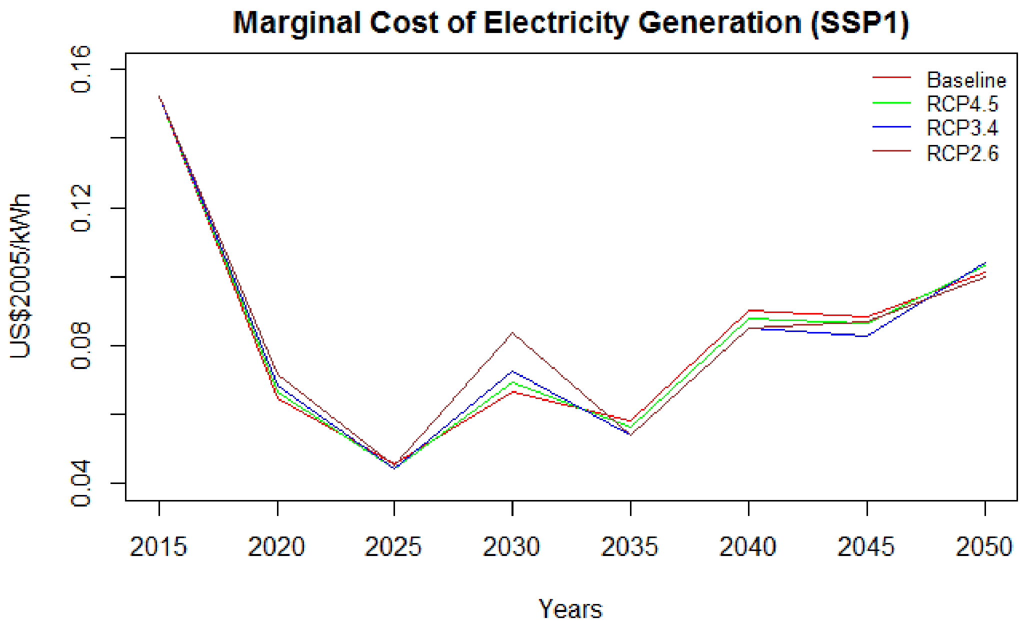

Figure 3.20: Marginal cost of electricity generation for SSP1

Electricity demand includes both seasonal and hourly load variations due to changes in electricity demand (Figure 2.2). The transformation of the electricity supply system is assessed first for 2035 which corresponds to the first commitment period of the Paris Agreement and 2050 as a result of net-zero carbon emission target of the UNFCCC [71]. These targets are based on CBDR and RC of countries as major emitting regions such as the USA, China and EU are expected to lead this climate ambition.

Arranging the load zones from peak to base load demand provides an insight to the selection of power generation technologies for load-follow requirements. The base load electricity demand for Baseline scenario in SSP1 is supplied mainly by coal and hydro power plants in 2035 (Figure 3.21).

The costs of renewable electricity decreases during the modeling period with solar power decreases at the highest rate. Rapid reduction of energy intensity of production prevents investments for nuclear energy whereas the high cost of geothermal power and internalization of the respective CO_2 emissions favors other renewable energy technologies.

The assumption for lower prices for extraction and import of coal favors continuing investments for both import and domestic coal fired power plants in 2035 (Figure 3.21). The increasing marginal costs together with decreasing costs of renewables are represented as penetration of solar and wind power in 2035. Hydro power contributes to electricity generation for base load demand and gas power for intermediate load with peak load supplied by wind and solar power together with electricity import.

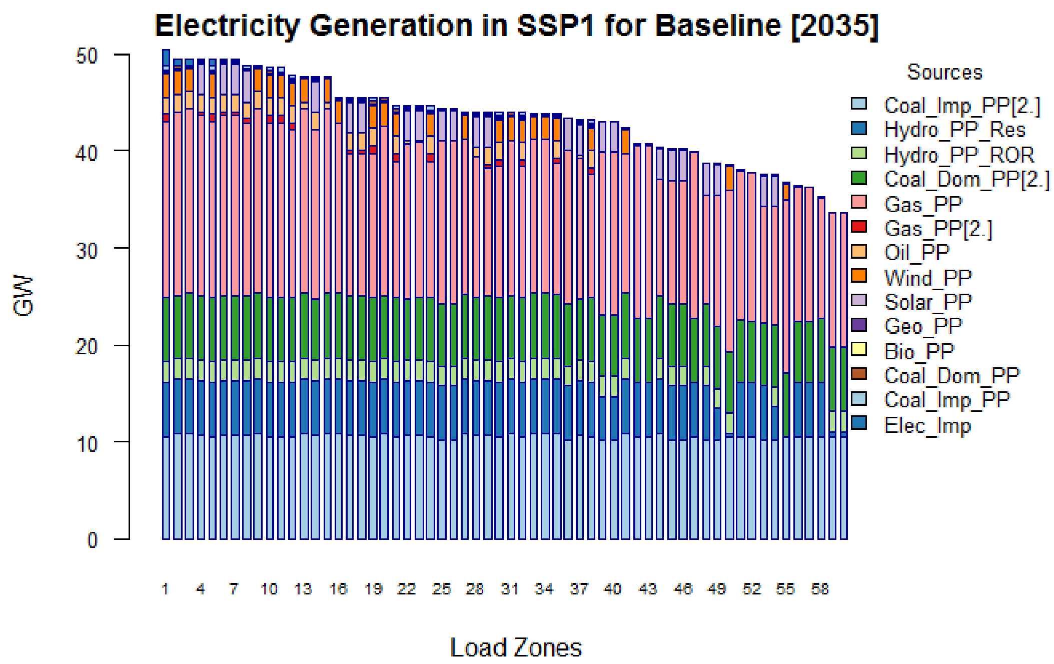

Figure 3.21: Electricity supply in SSP1 for Baseline [2035]

The transformation of power sector for RCP4.5 in SSP1 includes changes in medium and base load electricity demand in 2035. Hydro power is substituted by wind and solar power as a low carbon technology (Figure 3.22). Power generation from gas power plants shifts to both additions and subtractions in load regions as a result of high flexibility of this technology to supply demand load variations.

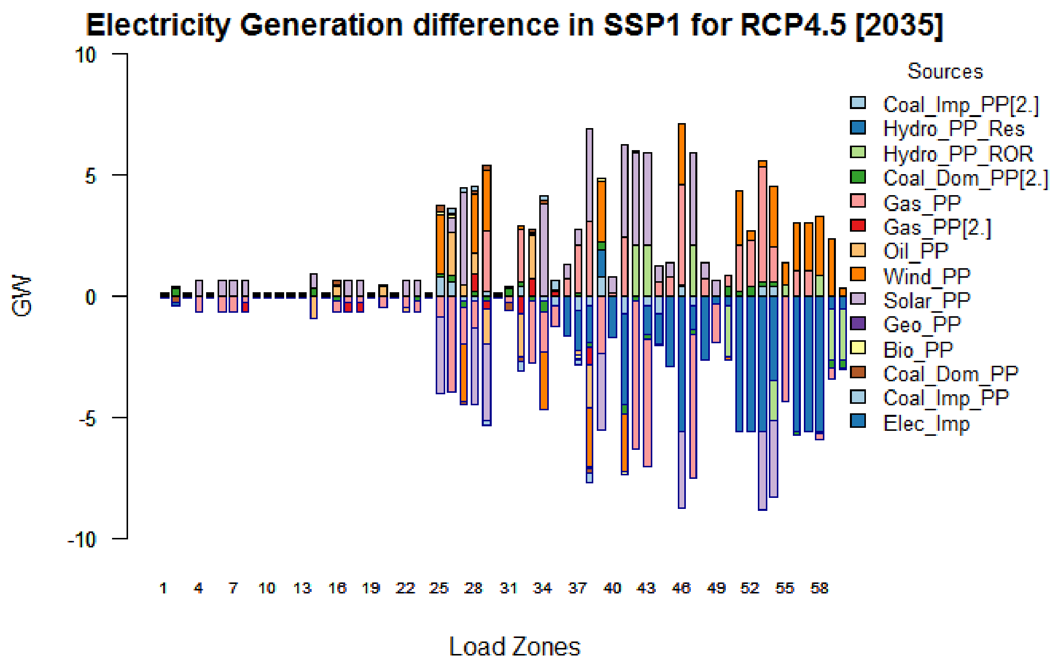

Figure 3.22: Electricity supply difference in SSP1 for RCP4.5 [2035]

Increasing the climate ambition to RCP3.4 in SSP1 increases the substitution of gas power in peak load demand by wind and solar power in 2035 (Figure 3.23). The intermittency of these renewable sources is a concern for peak load demand as the flexibility of gas power plants to supply both demand load fluctuations and also ancillary services are decreased in the energy supply system. This substitution is supported by minor reduction in both import and domestic coal power generation for transition to a low carbon energy system.

The most stringent climate target of RCP2.6 in SSP1 provides an already increasing penetration of wind and solar power for both peak and base load electricity demand (Figure 3.24). Together with this increase, gas power for both peak and base load demand and hydro power for base load demand are substituted by wind and solar power generation.

The transformation of the power sector for Baseline scenario in SSP1 includes the addition of NPPs as base load electricity generation in 2050 (Figure 3.25). The flexibility of gas power plants provides an opportunity for increasing usage of intermittent

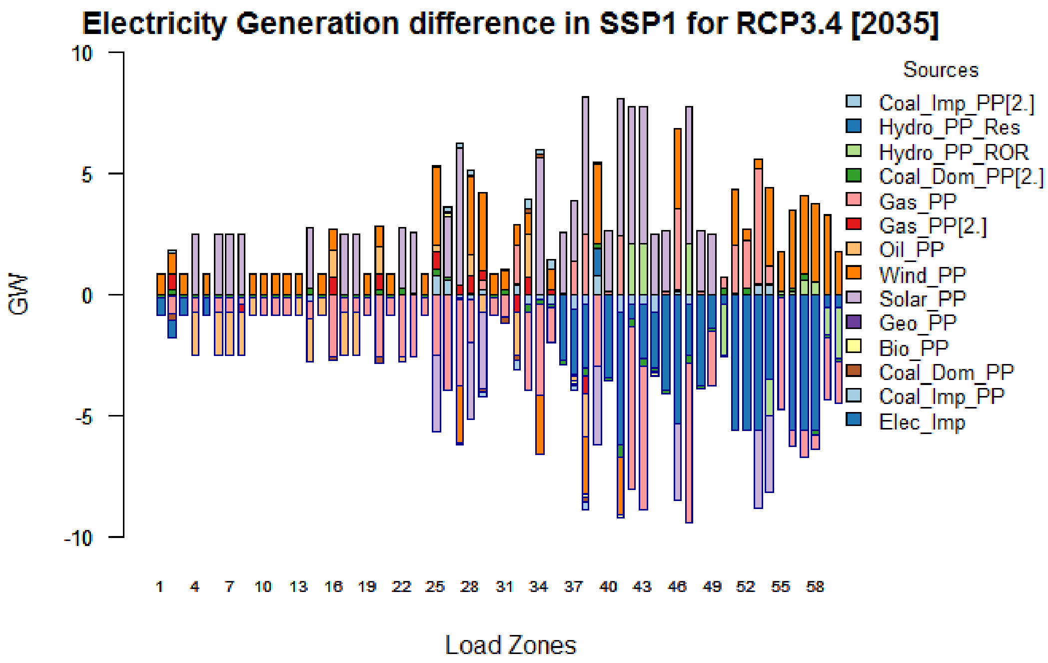

Figure 3.23: Electricity supply difference in SSP1 for RCP3.4 [2035]

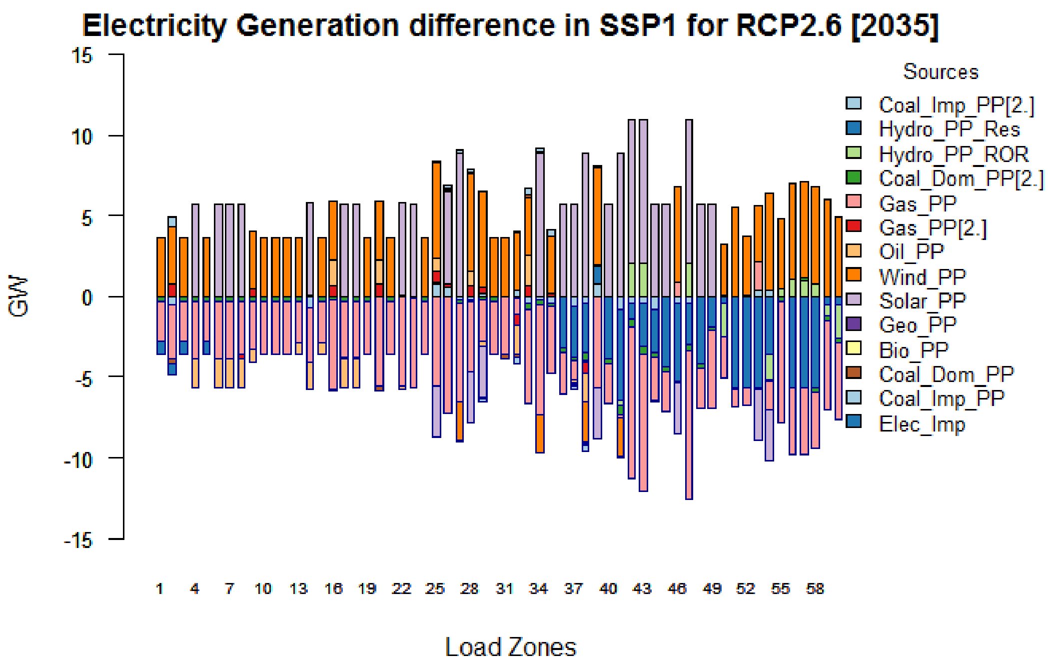

Figure 3.24: Electricity supply difference in SSP1 for RCP2.6 [2035]

wind and solar power for all load regions. Power supply system is dominated by technologies capable of providing both demand load fluctuations and also ancillary services therefore reducing concerns for grid flexibility.

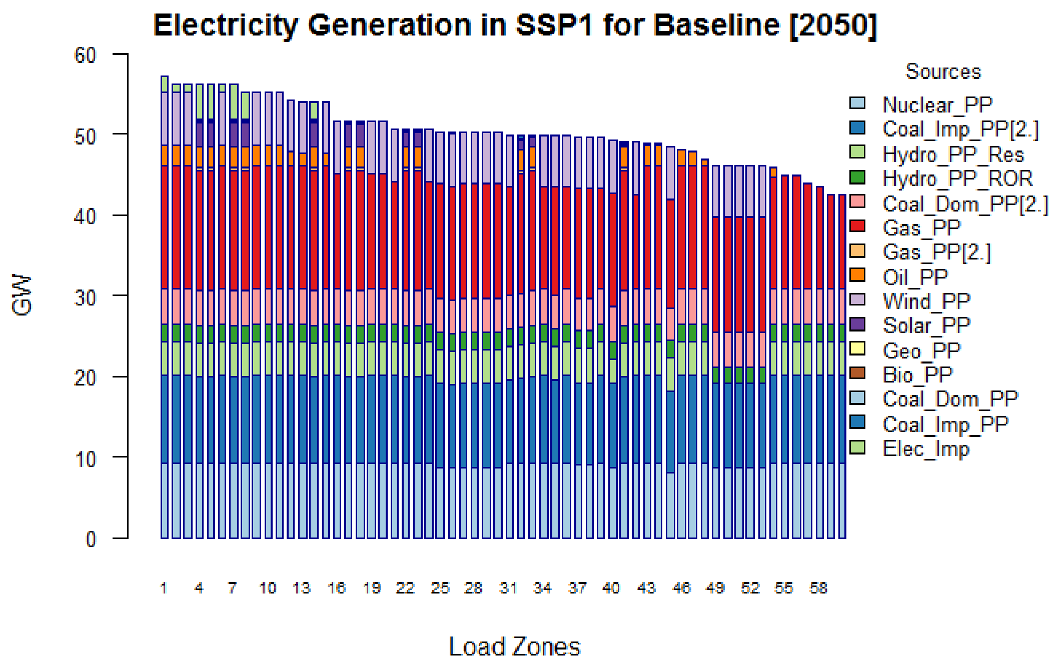

Figure 3.25: Electricity supply in SSP1 for Baseline [2050]

Implementing CO_2 emission penalty costs for RCP4.5 in SSP1 causes reduction in nuclear power for all load regions and hydro power for base load demand in 2050 (Figure 3.26). We expect increasing concerns for grid flexibility as NPPs which are available on demand are partially substituted by intermittent wind and solar power generation.

This substitution is increased further for higher CO_2 emission penalty costs in RCP3.4 (Figure 3.27) and RCP2.6 (Figure 3.28) as electricity generation from NPPs are decreased further. This situtation is in line with the assumptions for the energy system model based on SSP1 narrative providing higher energy efficiency improvements and higher capital cost reduction through learning by doing in renewable energy technologies.

The marginal cost of electricity for SSP2 increases in 2030 as a result of higher CO_2

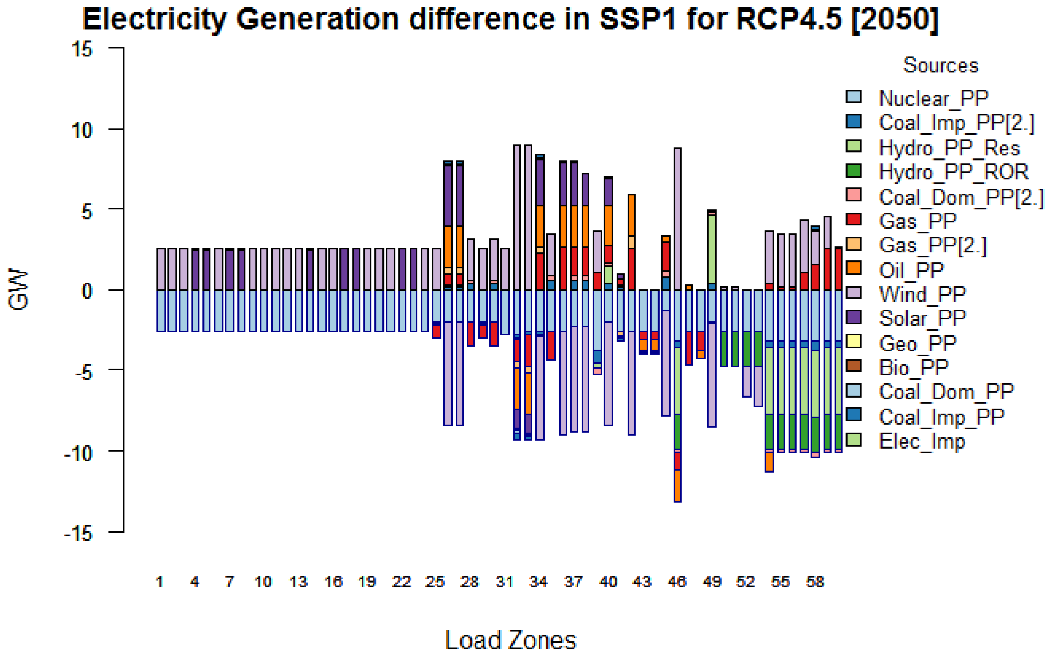

Figure 3.26: Electricity supply difference in SSP1 for RCP4.5 [2050]

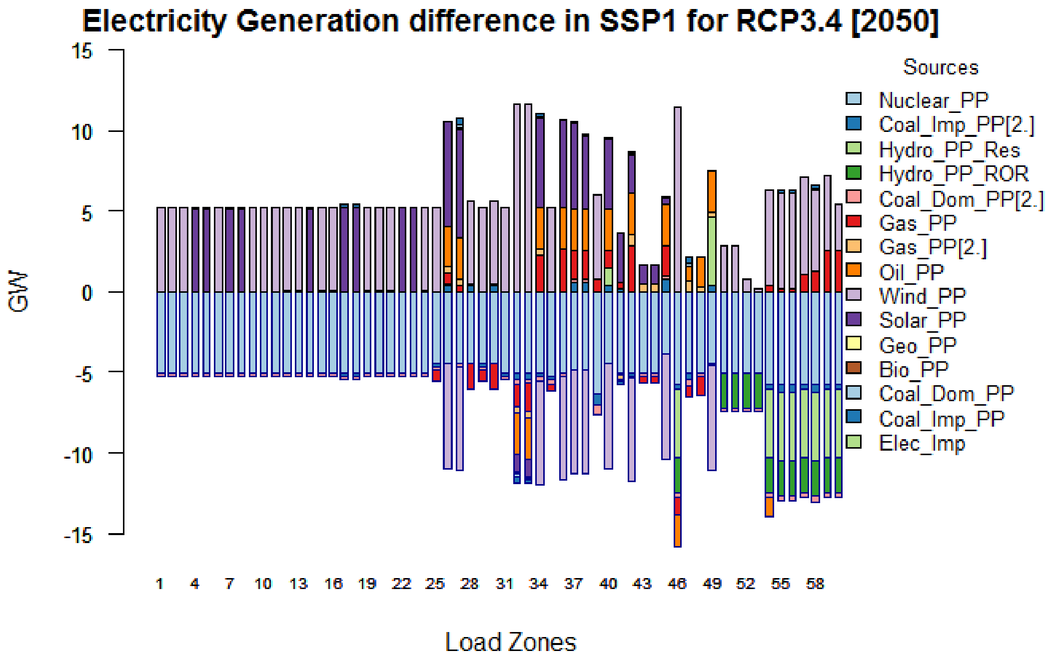

Figure 3.27: Electricity supply difference in SSP1 for RCP3.4 [2050]

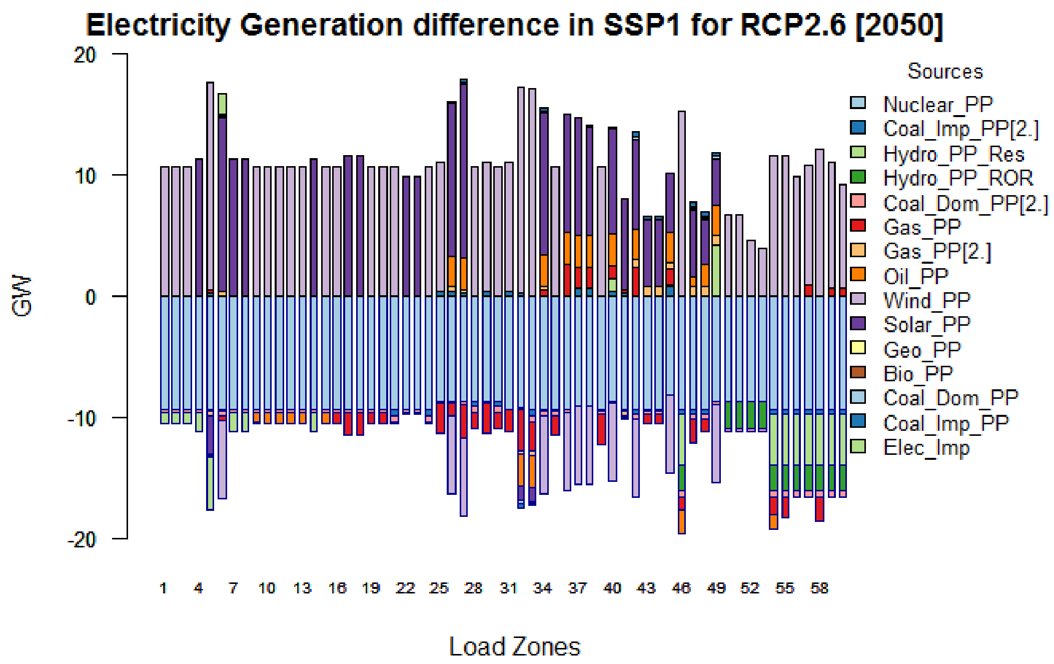

Figure 3.28: Electricity supply difference in SSP1 for RCP2.6 [2050]

emission penalty costs causing transformation to a low carbon energy system (Figure 3.29). Investments to power supply system for increasing final electricity demand are shifted to the end of the modeling horizon for decreasing climate amibition and Baseline scenarios. This also causes a carbon lock-in to fossil power generation for Baseline scenario during the modeling horizon.

Electricity generation for Baseline scenario in SSP2 includes small addition of NPP for baseload demand together with coal and hydro power plants in 2035 (Figure 3.30). The flexibility of gas power plants supports the penetration of wind and solar power together with electricity import for peak load demand.

The small addition of NPP for Baseline scenario in SSP2 is substituted by wind and solar power for RCP6.0 in 2035 (Figure 3.31). The flexibility of gas and oil power plants supports the transformation of power sector to low carbon system providing penetration of additional renewable energy sources. Electricity generation from hydro power with reservoir is reduced whereas ROR hydro power generation is configured based on the availability of wind and solar power.

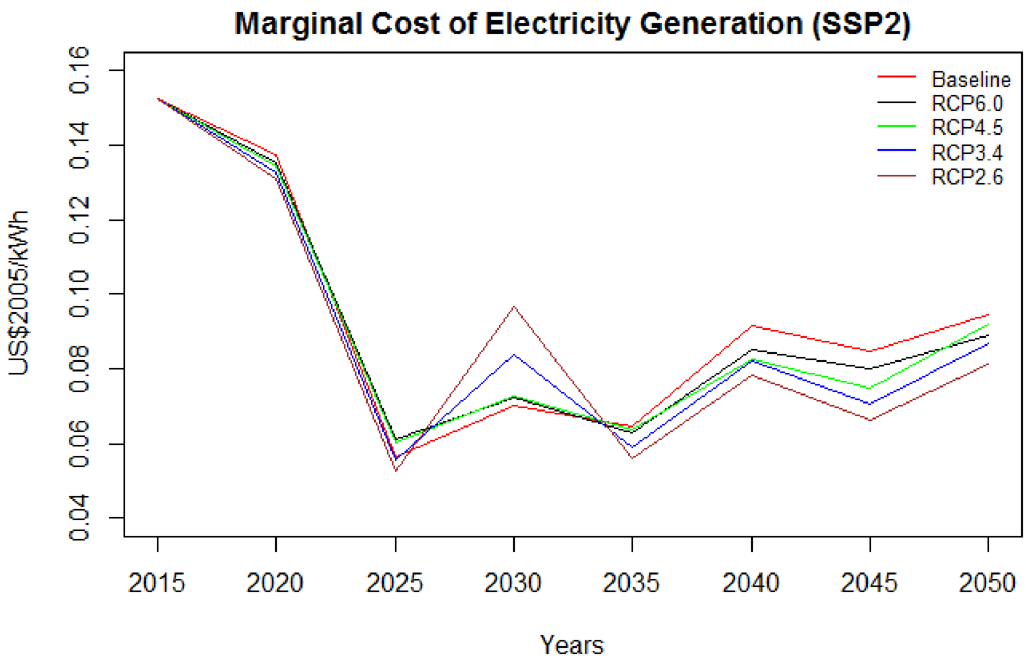

Figure 3.29: Marginal cost of electricity generation for SSP2

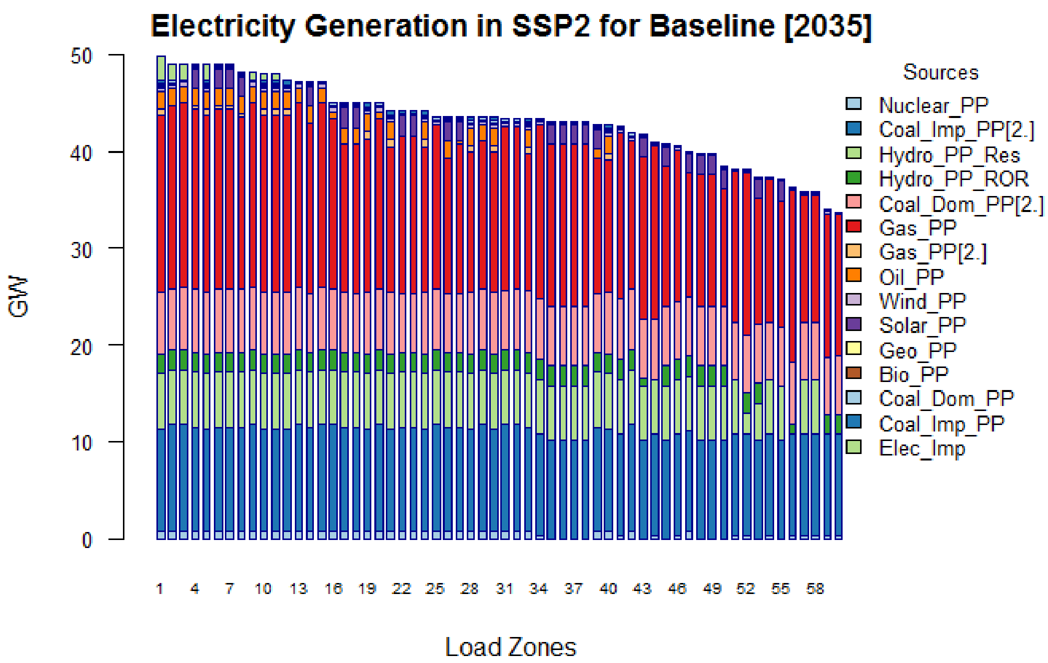

Figure 3.30: Electricity supply in SSP2 for Baseline [2035]

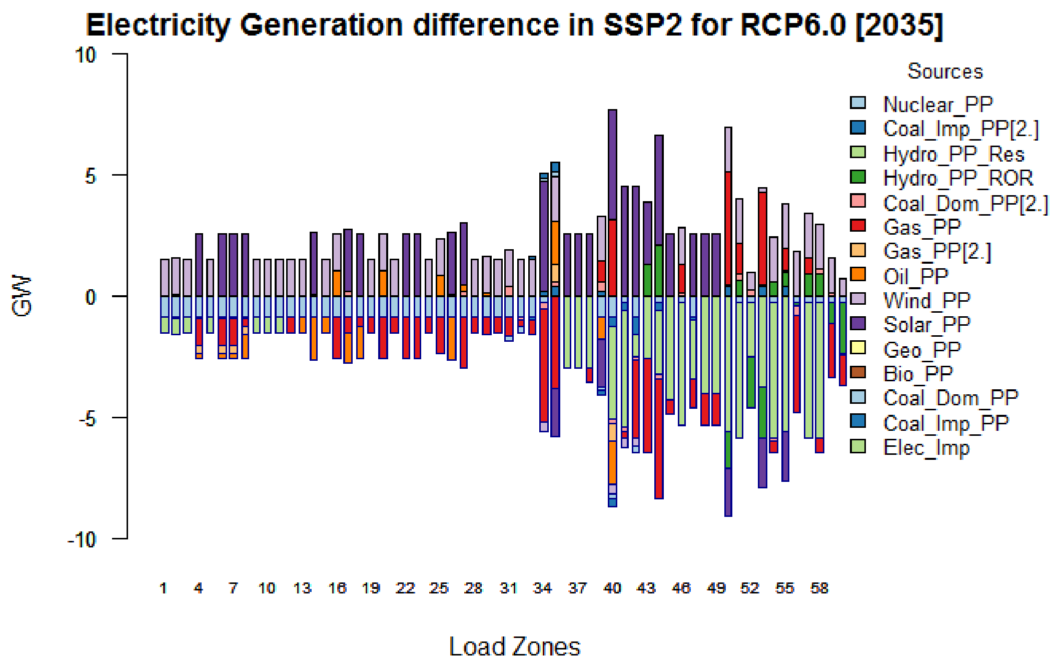

Figure 3.31: Electricity supply difference in SSP2 for RCP6.0 [2035]

Increasing the climate ambition further to RCP4.5 results in additional substitution of gas and oil power plants with wind and solar power generation in 2035 (Figure 3.32). This causes reduction in flexibility of electricity grid to supply peak load as the capability to supply demand load fluctuations and ancillary services are reduced. Similarly the small addition of NPP is removed by substituting wind and solar power generation. This substitution of gas and oil power plants is increased for RCP3.4 therefore increasing further the concerns for grid flexibility to supply peak load demand (Figure 3.33).

The most stringent climate target of RCP2.6 in SSP2 protects the initial investment for NPP substituting carbon intensive electricity production from domestic coal power plants in 2035 (Figure 3.34). Additional power generation from solar and wind power plants exceeds 10 GW for all load regions substituting mainly electricity generation from gas power plants. The removal of grid flexibility and ancillary services by gas power plants causes concern as substituting solar and wind power are intermittent which requires flexibility mechanisms such as power plants with high flexibility, energy storage, demand side management and grid capacity extensions [155].

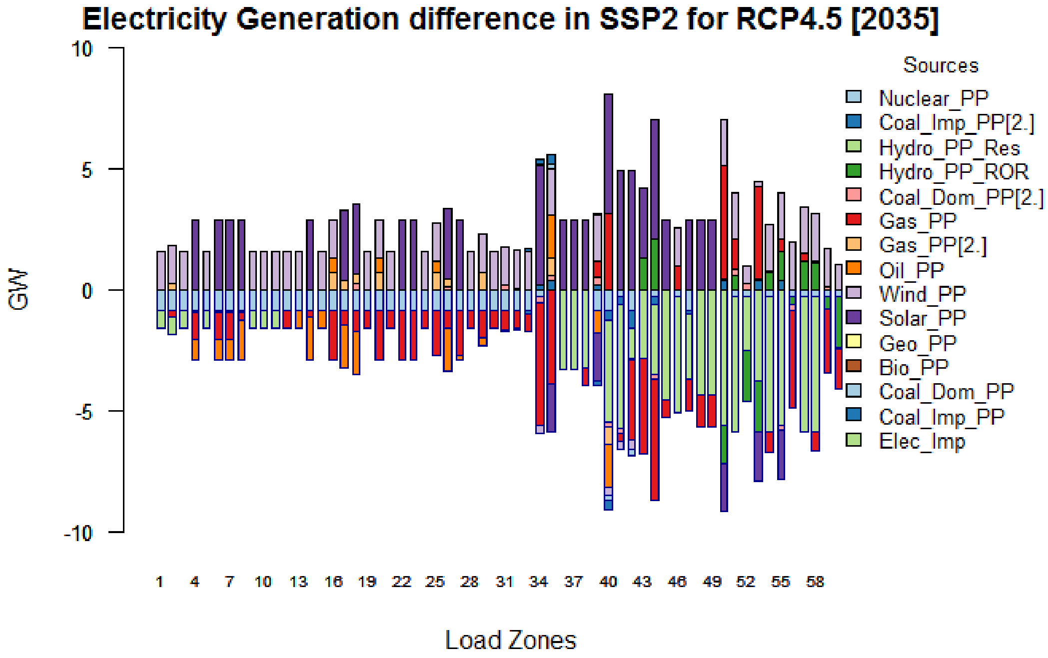

Figure 3.32: Electricity supply difference in SSP2 for RCP4.5 [2035]

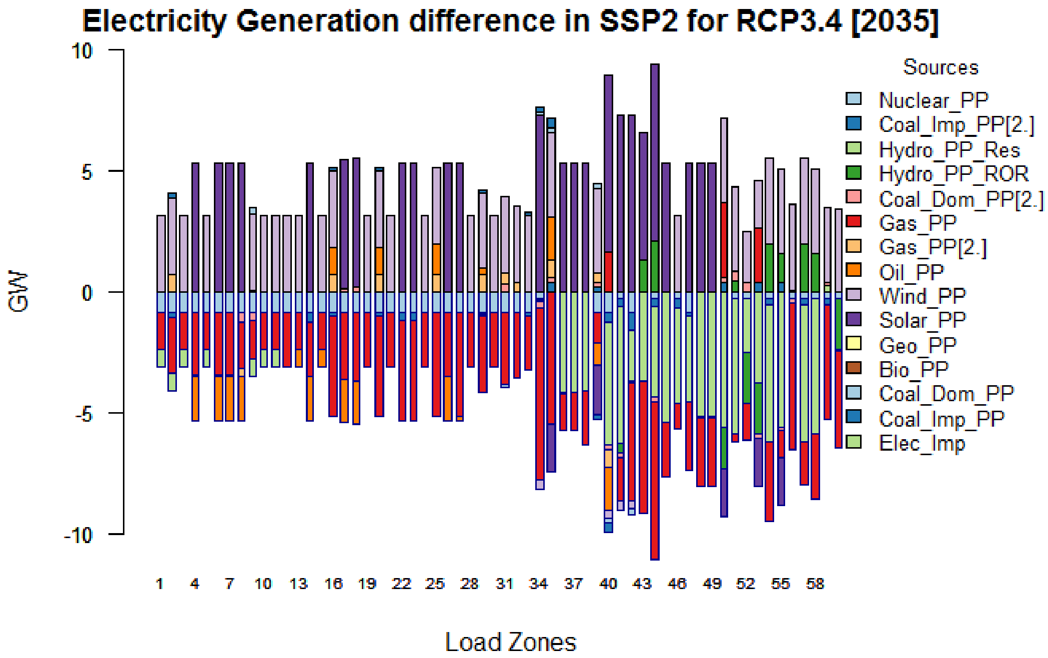

Figure 3.33: Electricity supply difference in SSP2 for RCP3.4 [2035]

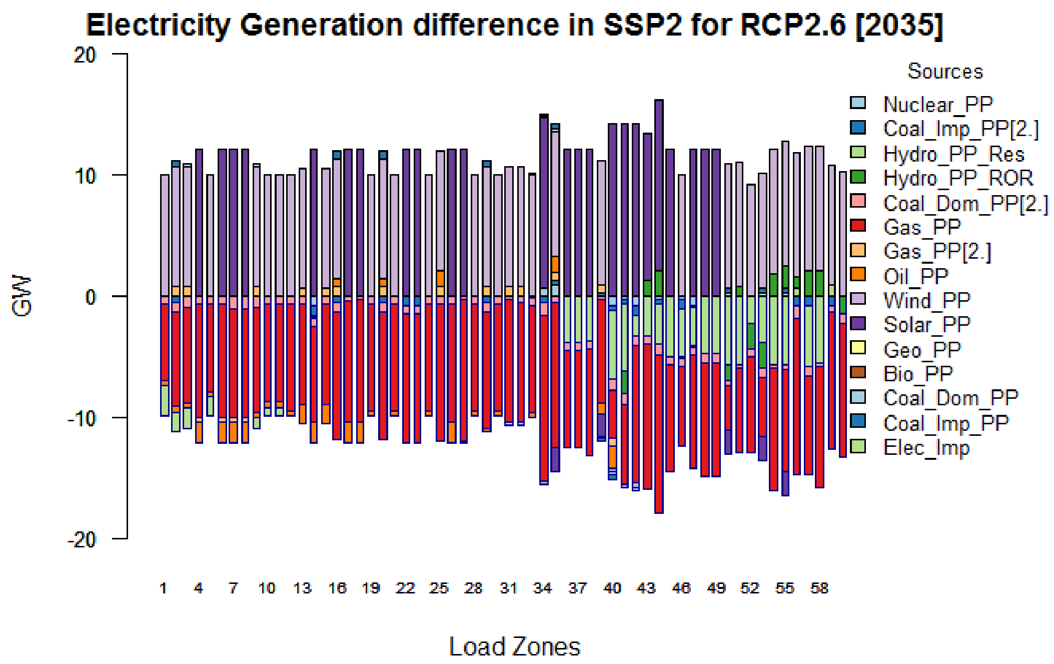

Figure 3.34: Electricity supply in SSP2 for RCP2.6 [2035]

The transformation of the power system for Baseline scenario in SSP1 is limited with small amount of wind and solar power generation for intermediate and peak load demand in 2050 (Figure 3.35). Electricity generation from NPPs increases further to 10 GW contributing to base load final electricity demand together with coal and hydro power plants. The flexibility of gas power plants provides opportunity for penetration of wind and solar power together with import electricity for peak load demand.

The penetration of NPP is reduced for RCP6.0 in SSP2 substituted by additional wind and solar power as low carbon energy sources in 2050 (Figure 3.36). Electricity generation from gas and hydro power plants are further subsituted by intermittent solar and wind power generation increasing concerns for grid flexibility to supply peak load demand.

The substitution of electricity generation from gas power plants for wind and solar power in 2050 is reduced for RCP4.5 in SSP2 (Figure 3.37). This decrease is compensated by increasing substitution of electricity generation from NPPs by intermittent wind and solar power plants reaching additional 10 GW in all load regions. The main

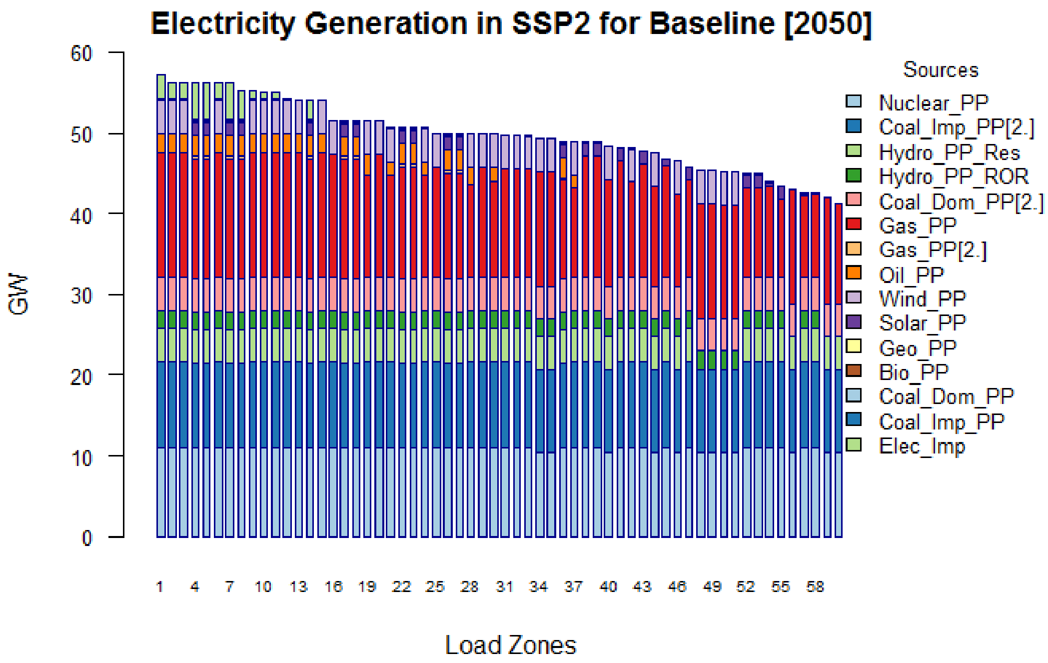

Figure 3.35: Electricity supply in SSP2 for Baseline [2050]

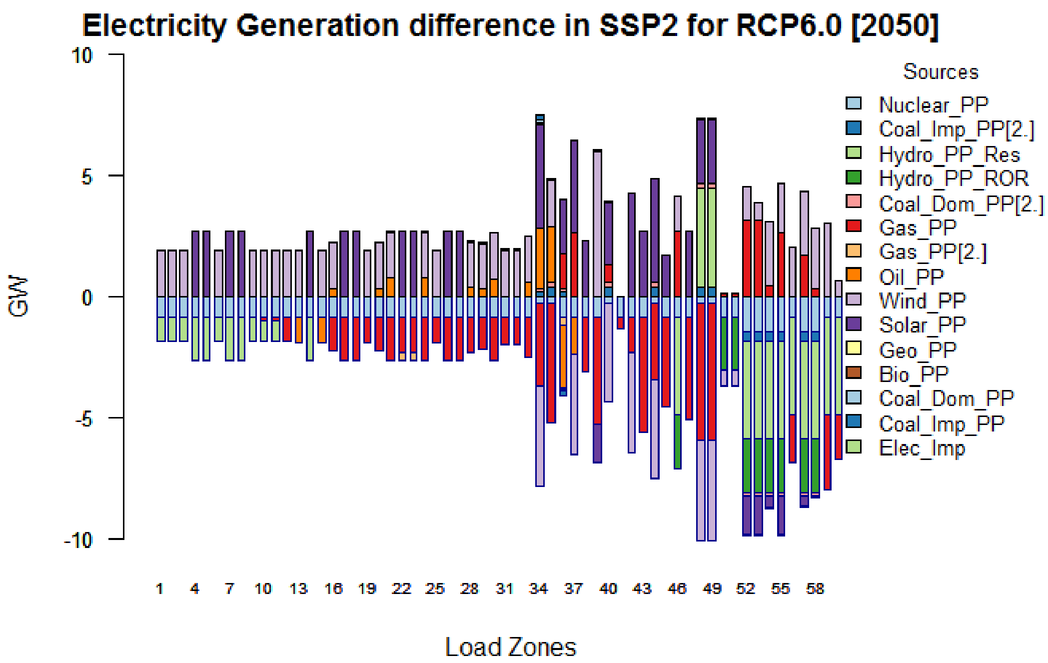

Figure 3.36: Electricity supply difference in SSP2 for RCP6.0 [2050]

reason for this change is the requirement of flexibility by gas power plants to supply peak load demand and ancillary services. The substitution of NPPs by wind and solar power increases further to 10 GW for RCP3.4 in SSP2 for low carbon transition of the energy supply system (Figure 3.38).

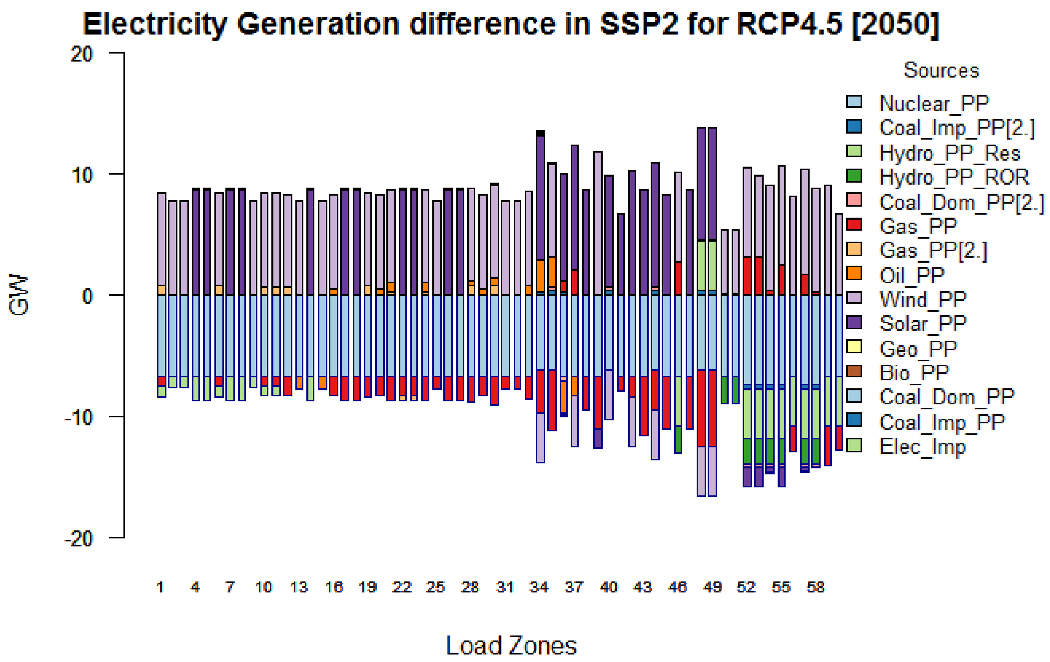

Figure 3.37: Electricity supply difference in SSP2 for RCP4.5 [2050]

The achievement of the most stringent climate target of RCP2.6 in SSP2 requires the substitution of all NPP capacity in Baseline scenario and large part of gas power generation reaching 10 GW in 2050 (Figure 3.39). Additional wind and solar power generation reaches 20 GW in all load regions causing concerns for grid flexibility to supply demand load fluctuations and also ancillary services.

SSP3 is characterized with high growth in population, low decrease in energy intensity of production and the rate of increase in GDP reaching a plateau by the end of the modeling period. Investments to supply increasing final electricity demand are supplied during beginning and end of the modeling horizon for Baseline and in 2030 for RCP scenarios due to increasing costs of CO_2 emission penalties (Figure 3.40).

The penetration of nuclear energy starts in the beginning of the modeling horizon in

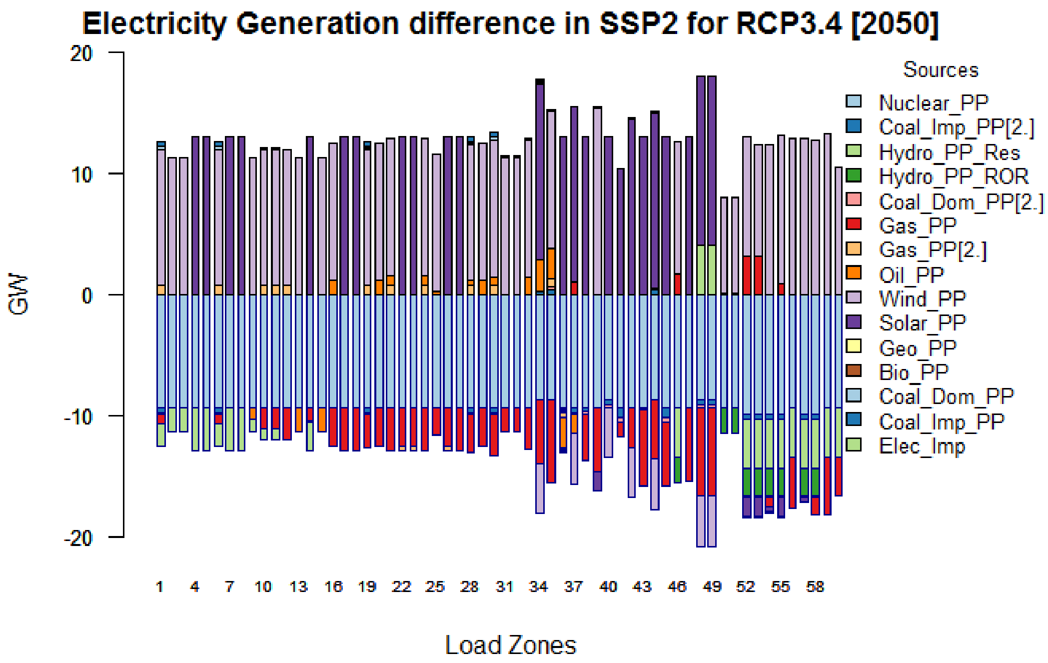

Figure 3.38: Electricity supply difference in SSP2 for RCP3.4 [2050]

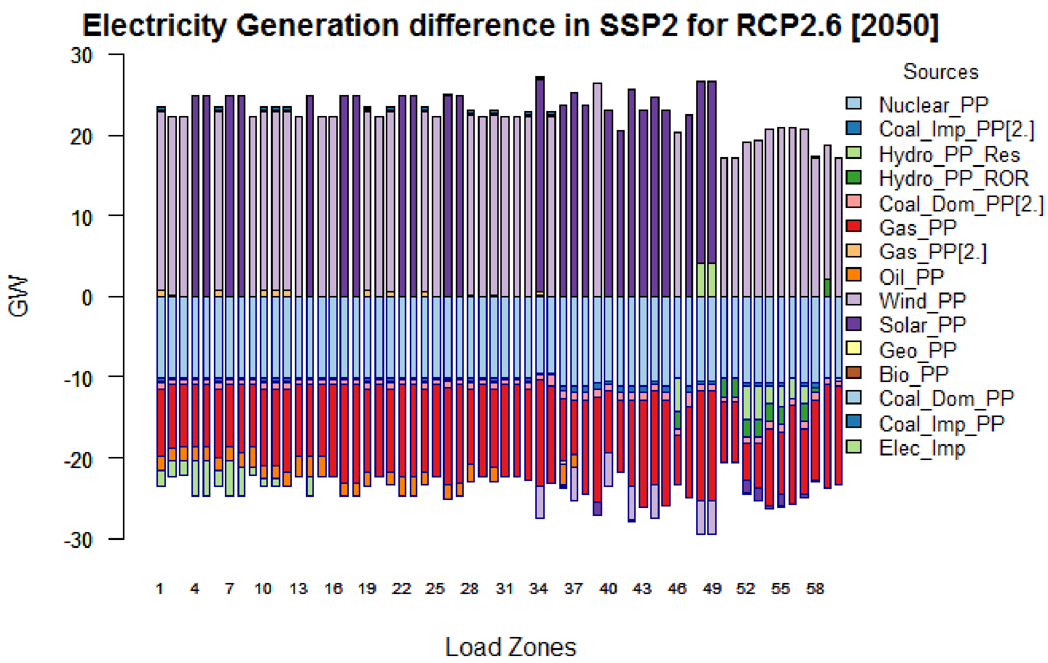

Figure 3.39: Electricity supply in SSP2 for RCP2.6 [2050]

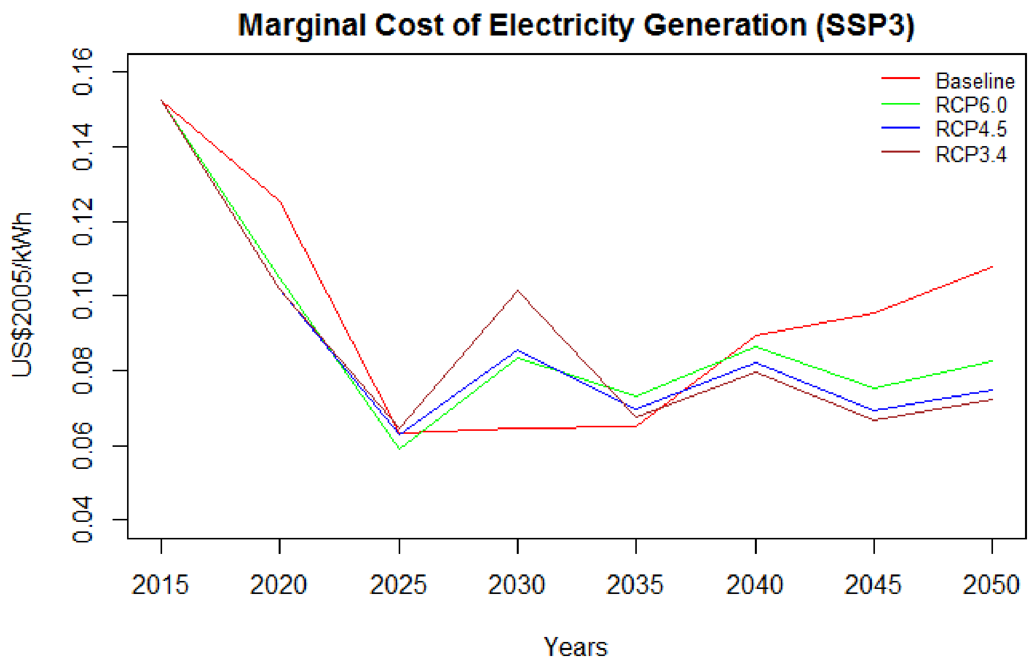

Figure 3.40: Marginal cost of electricity generation for SSP3

SSP3 for supplying base load electricity demand for Baseline scenario in 2035 (Figure 3.41). The remaining base load electricity demand is supplied by import coal power plants and hydro power. Flexibility requirements to supply demand load fluctuations are supplied by gas and domestic coal power plants with limited wind and solar power generation for intermediate and peak load demand.

Introduction of CO_2 emission penalty costs for RCP6.0 in SSP3 causes substitution of large part of NPPs with intermittent wind and solar power generation in 2035 (Figure 3.42). Electricity generation from hydro power is also reduced for base load demand increasing concerns for grid flexibility to supply demand load fluctuations. Increasing the climate ambition further to RCP4.5 includes substitution of import coal power plants with additional wind and solar power generation (Figure 3.43).

Additional electricity generation from wind and solar power plants for RCP3.4 in SSP3 reaches 10 GW for all load regions in 2035 (Figure 3.44). Power generation from import coal power plants and gas power plants are further substituted by wind and solar power generation. Electricity generation from NPPs are similarly substi-

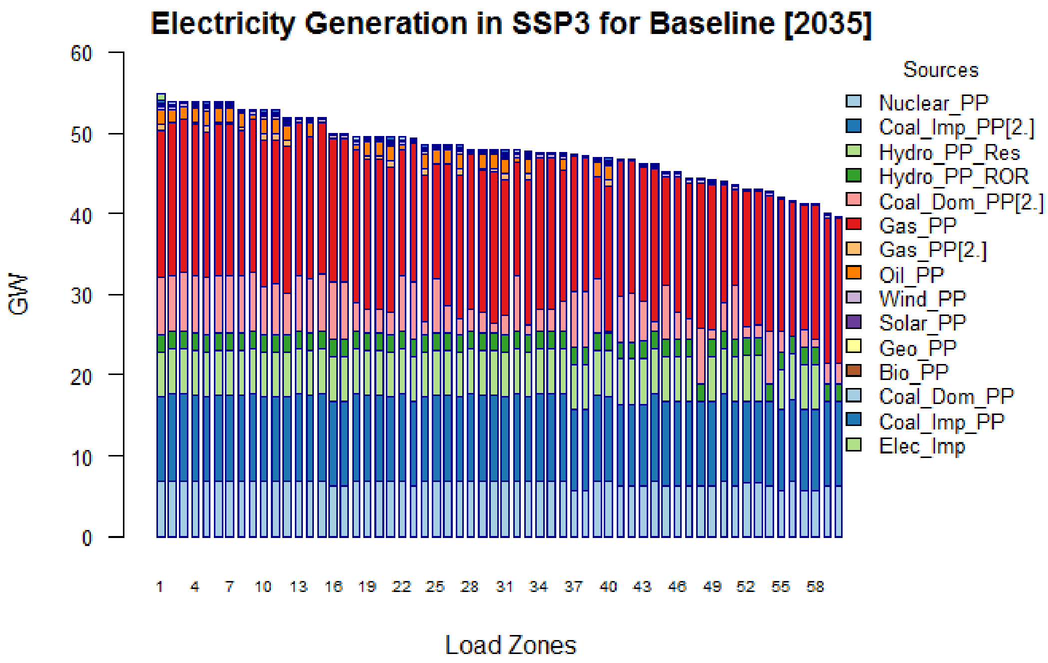

Figure 3.41: Electricity supply in SSP3 for Baseline [2035]

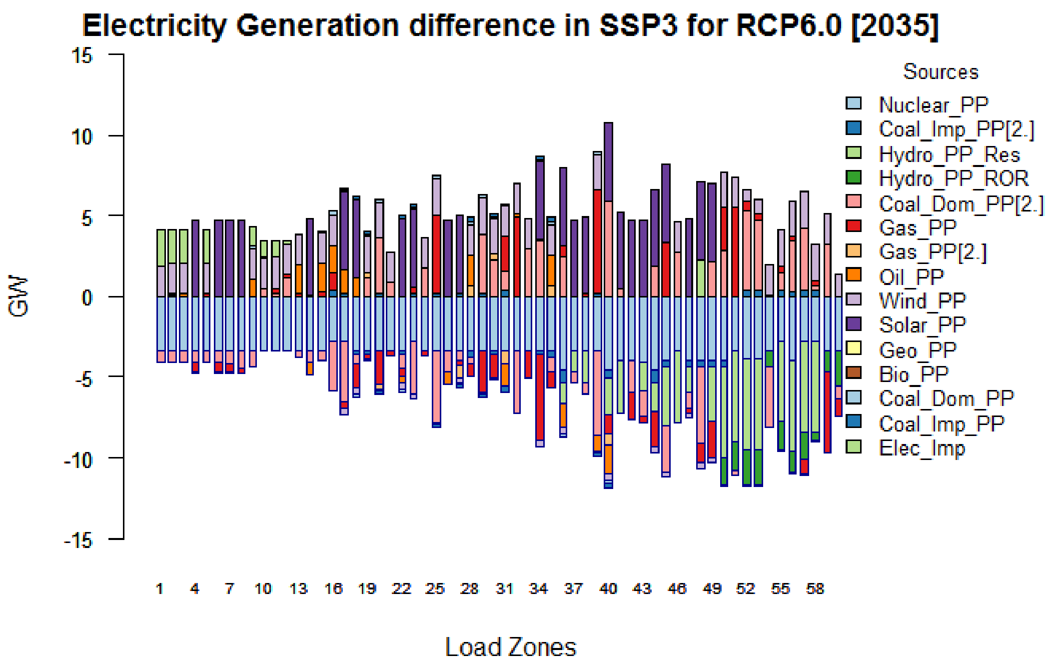

Figure 3.42: Electricity supply difference in SSP3 for RCP6.0 [2035]

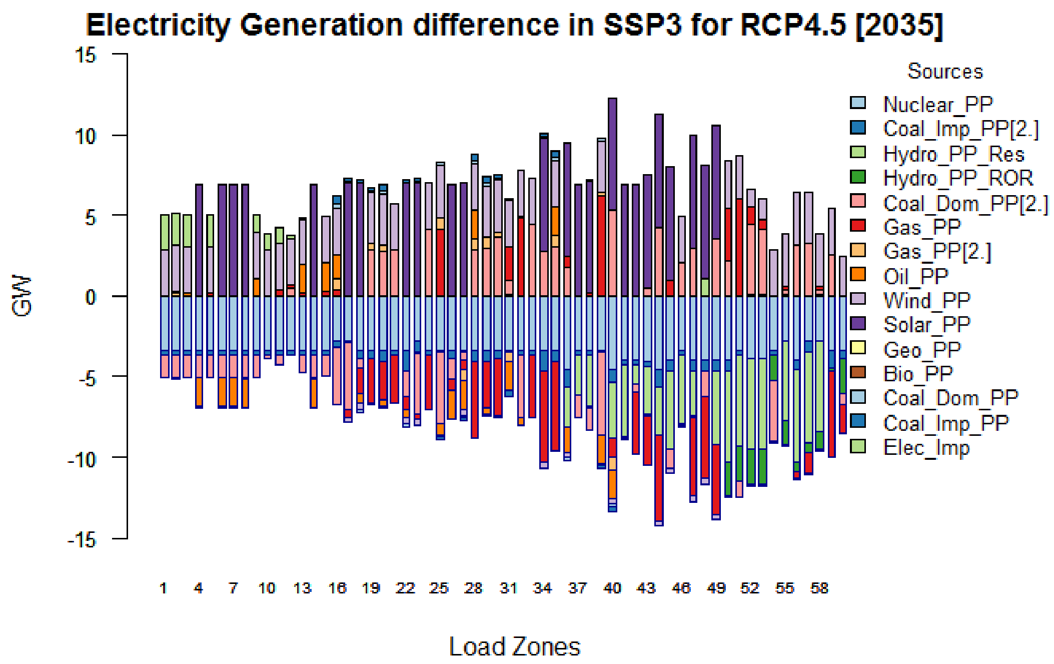

Figure 3.43: Electricity supply difference in SSP3 for RCP4.5 [2035]

tuted by renewable energy technologies for low carbon transition of the energy supply system.

Base load electricity demand for Baseline scenario in SSP3 includes NPPs reaching 10 GW together with coal and hydro power plants in 2050 (Figure 3.45). Electricity generation from gas power plants supply intermediate load demand without requirements for flexibility to supply demand load fluctuations. There is additional contribution of oil power plants with flexible diesel generations for supplying flexibility requirements for additional wind and solar power generation. The peak load demand includes supply of import electricity to meet increasing demand for final electricity.

Increasing the CO_2 emission penalty cost for RCP6.0 in SSP3 causes the partial substitution of electricity generation from NPPs, hydro power and gas power plants with intermittent solar and wind power generation in 2050 (Figure 3.46). In addition to this, there is small substituion of coal power plants for renewable energy technologies for low carbon transition of the energy supply system.

The additional capacity of wind and solar power generation for RCP4.5 in SSP3

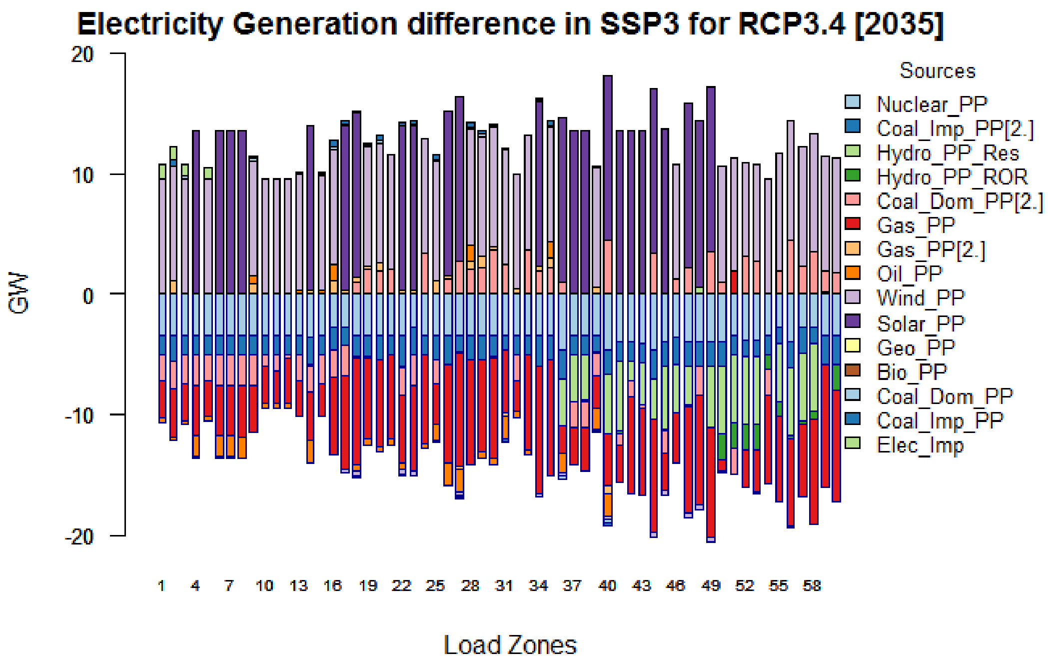

Figure 3.44: Electricity supply in SSP3 for RCP3.4 [2035]

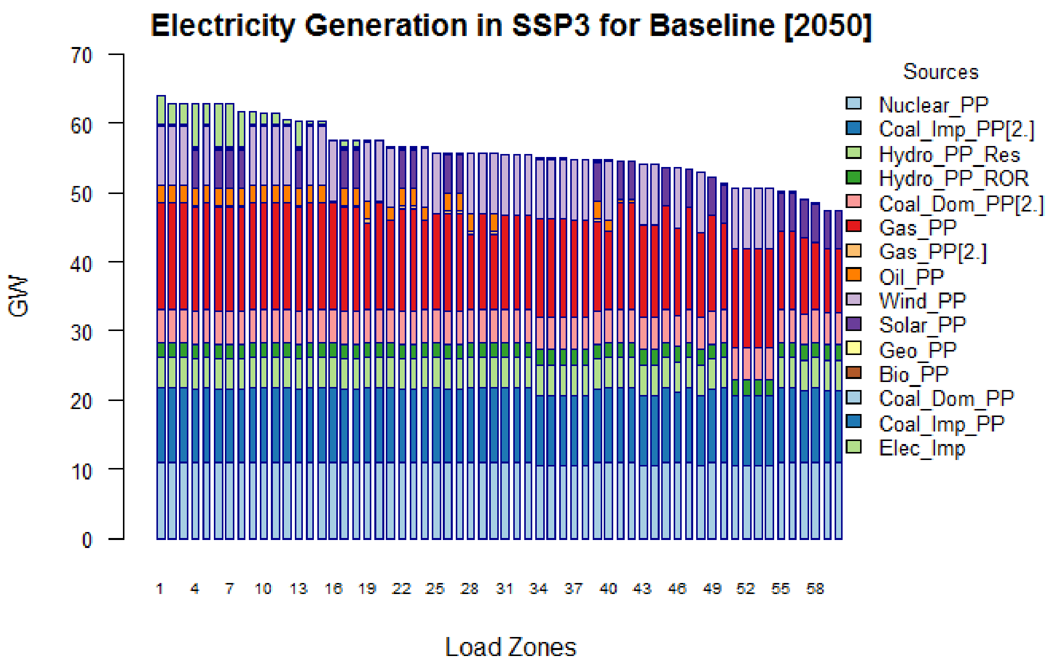

Figure 3.45: Electricity supply in SSP3 for Baseline [2050]

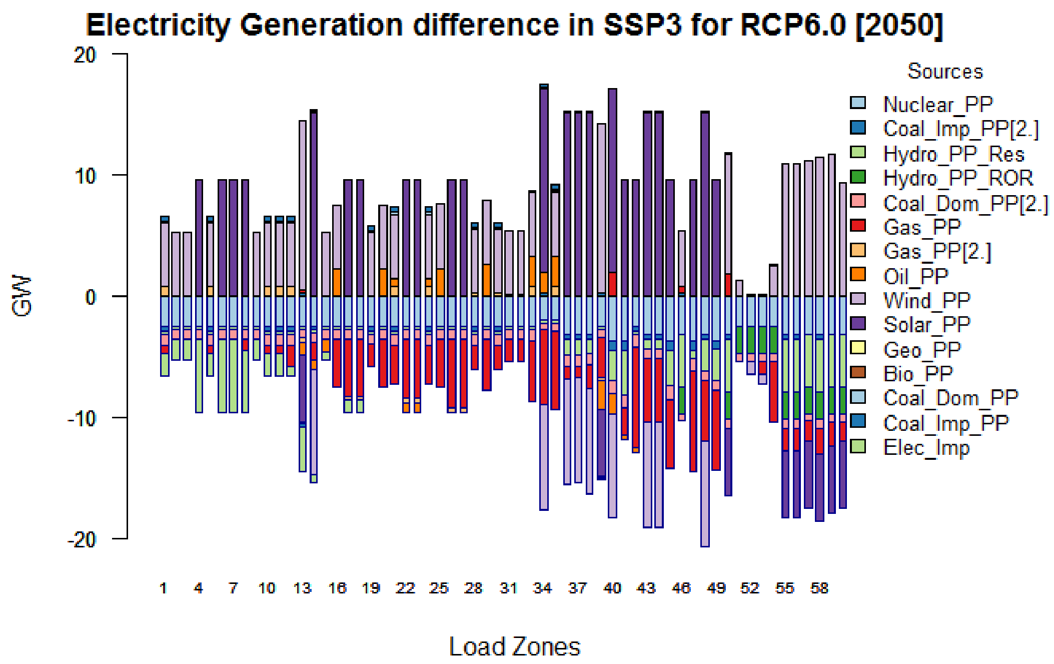

Figure 3.46: Electricity supply in SSP3 for RCP6.0 [2050]

reaches 20 GW in 2050 (Figure 3.47). There is also an increasing substitution of electricity generation from NPPs and gas power plants for renewable energy technologies for low carbon transition of the energy supply system. Increasing the climate ambition further for RCP3.4 in SSP3 includes additional substitution of coal power plants for solar and wind power generation reaching additional 30 GW in all load regions (Figure 3.48).

The main assumption on the usage of FITs collected from emission penalties to renewable energy generation causes the increasing penetration of solar power for RCPs in all SSP scenarios [92]. This subsidy causes partial substitution of electricity generation from NPPs as the costs of electricity generation from renewable energy technologies are reduced and the availability of input energy is higher compared to other technologies. The marginal costs of electricity generation provide price signals for selection of the power generation technology for supplying increasing final electricity demand. The definition of separate load regions for wind and solar power prevent competition between these technologies as they supplement each other for low carbon transition of the energy system.

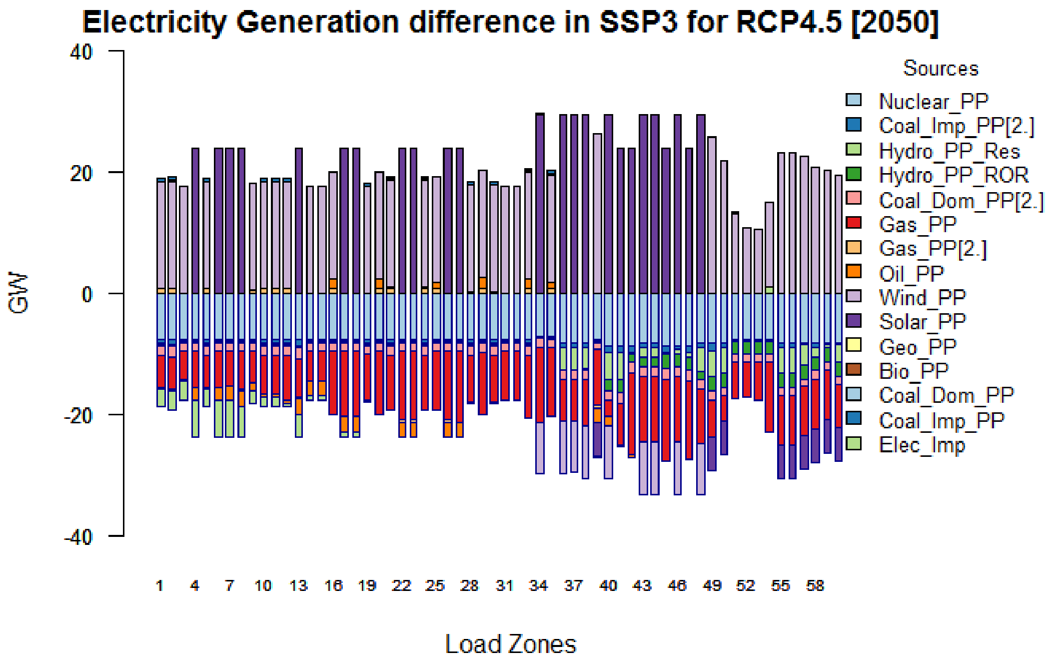

Figure 3.47: Electricity supply in SSP3 for RCP4.5 [2050]

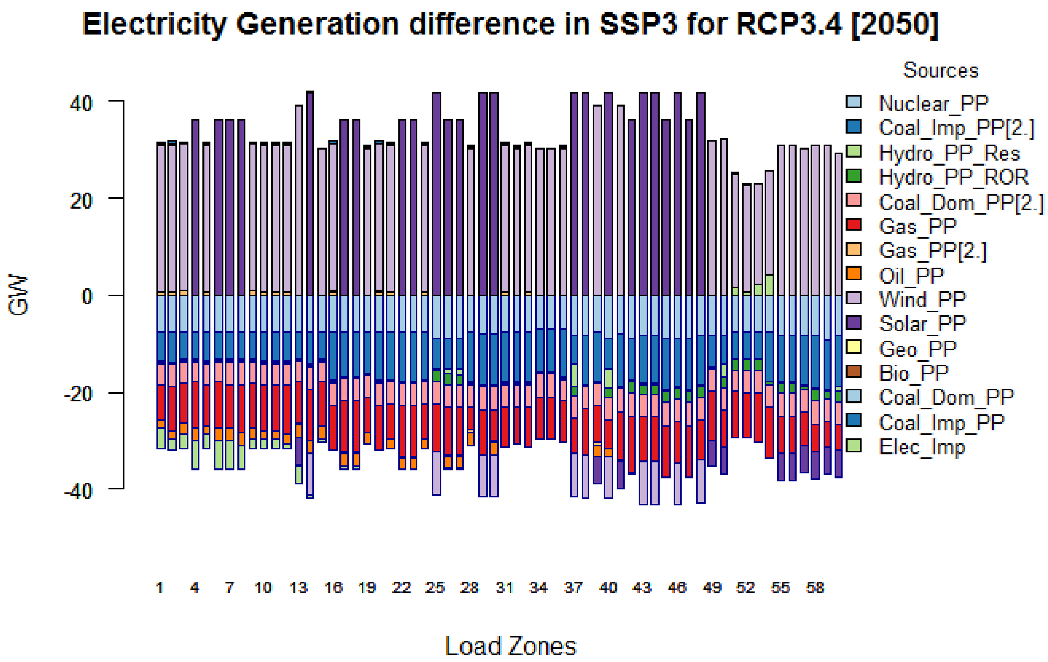

Figure 3.48: Electricity supply in SSP3 for RCP3.4 [2050]

3.1.4 Electricity grid flexibility

The flexibility of the electricity grid is defined as the required reserve capacity to supply the peak demand for final electricity. The flexibility of the grid to supply peak load demand in all load regions decreases from above 50% in 2015 to below 30% in SSP1 for Baseline scenario and climate targets of RCP4.5 and RCP3.4 in 2050 (Figure 3.49). The most ambitious climate target of RCP2.6 in SSP1 includes additional 10 GW capacity investment to wind and solar power generation reducing further the flexibility to 20% which is increased to 30% by 2050 with additional power generation from oil power plants (Figure 3.28).

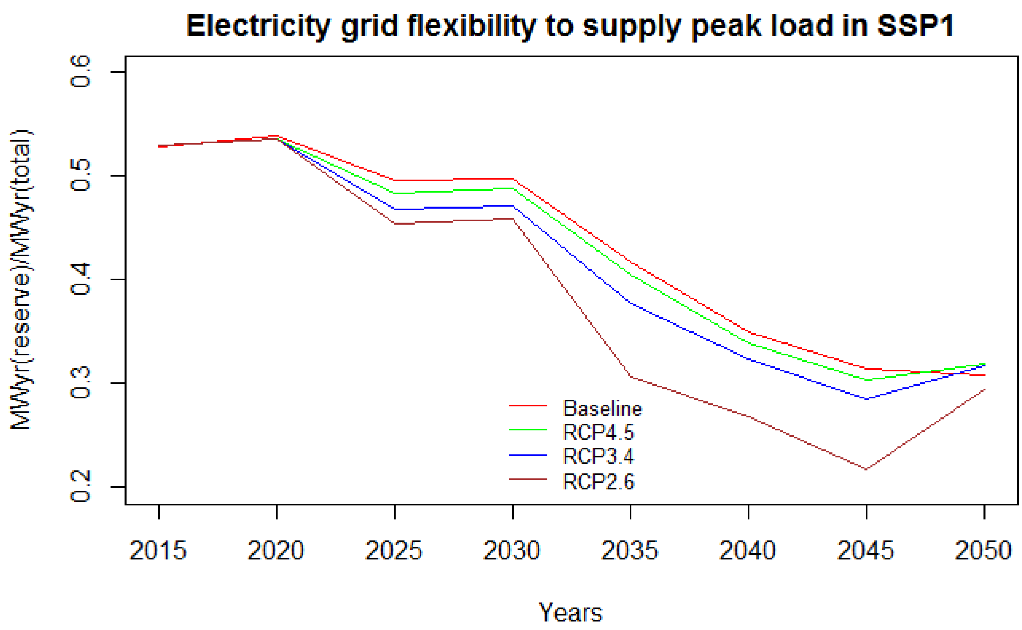

Figure 3.49: Annual electricity grid flexibility to supply peak load in SSP1

The reduction of grid flexibility to supply peak load electricity demand is similar in SSP2 for Baseline scenario and climate targets of RCP6.0, RCP4.5 and RCP3.4 reducing from above 50% in 2015 to approximately 30% in 2050 (Figure 3.50). The flexibility of the grid for the most ambitious climate scenario of RCP2.6 is reduced gradually from above 50% in 2015 to 20% in 2035 and further below 10% in 2045. The additional electricity generation from wind and solar power for RCP2.6 is 10

GW in 2035 (Figure 3.34) and 20 GW in 2050 (Figure 3.39) without additional fossil power generation to increase the flexibility of the grid to supply peak load electricity.

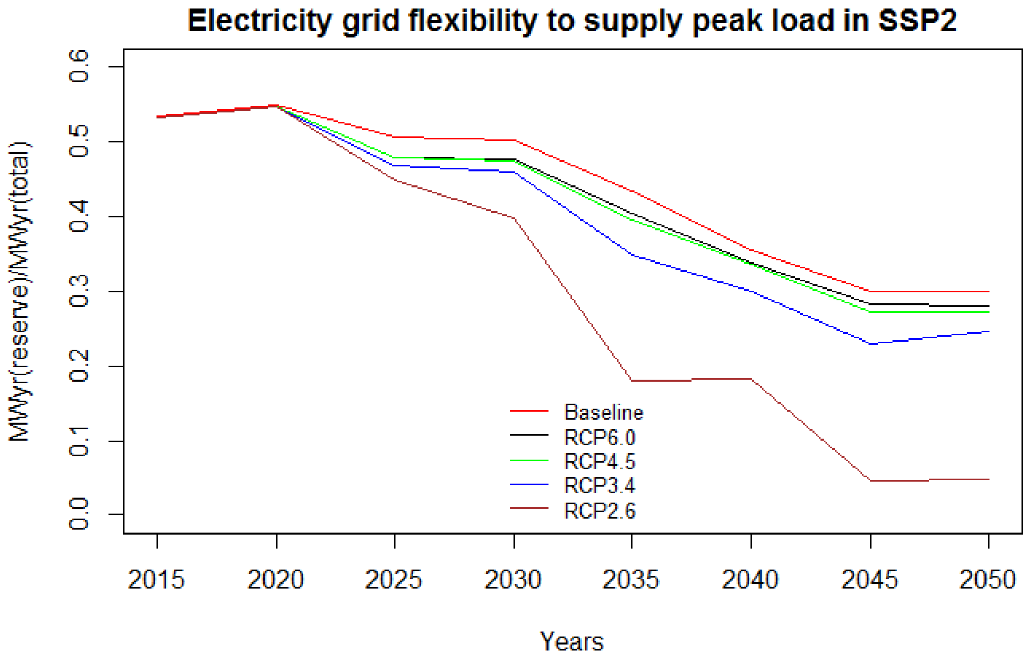

Figure 3.50: Annual electricity grid flexibility to supply peak load in SSP2

The grid flexibility in SSP3 is reduced from 50% in 2015 to above 20% for Baseline scenario and climate target of RCP6.0 (Figure 3.51). For the most stringent climate targets of RCP4.5 and RCP3.4 in SSP3 the flexibility requirements reduce to below 10% which requires demand side management as the load factor of final electricity demand in reference year 2014 is 85% requiring at least 15% reserve capacity for peak load demand not including ancillary services (Figure 2.4). The additional generation capacity of wind and solar power is more than 20 GW for RCP4.5 (Figure 3.47) and reaches 40 GW for RCP3.4 (Figure 3.48) in 2050 reducing the flexibility of grid due to intermittency of these energy sources.

The flexibility of the grid protects the electricity supply system from peak demand exceeding supply, transmission system failures and primary and secondary regulation to supply electricity at required voltage and frequency. The impact of electricity grid flexibility can be further assessed using system dynamic modeling tools for deployment of large scale variable renewable energy sources [55]. The benefit of this

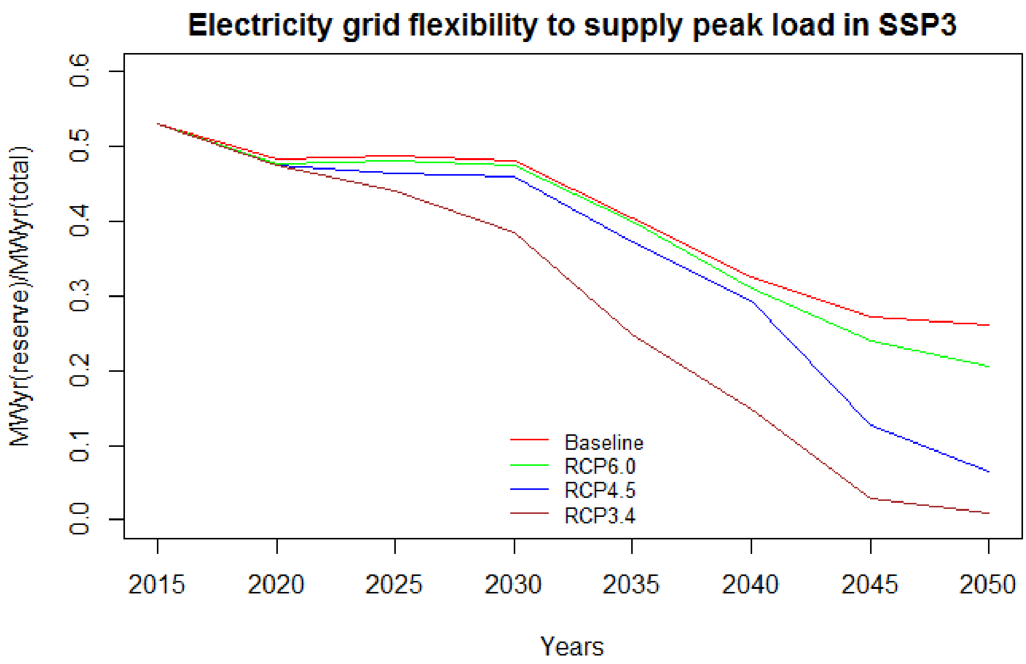

Figure 3.51: Annual electricity grid flexibility to supply peak load in SSP3

approach would be to integrate the energy system as a network of relations including the deployment and adoption of innovative technologies and related services such as digitalization and smart grid applications.

3.1.5 Atmospheric gas emissions

The CO_2 emissions from power sector include both direct emissions from combustion of fossil fuels and indirect emissions from upstream activities including resource extraction and conversion to secondary energy sources [82]. The size of the power plants also has affect on land use which can be higher for large hydro-power plants or solar PV with large installed capacity causing both aesthetic impacts and also having impact on land-atmosphere coupling [30]. The life-cycle CO_2 emissions from power sector are included in Figure 3.9.

Total CO_2 emission from energy supply system also includes emissions from final energy demand which reduces the carbon budget available for climate mitigation.

Table 3.9: CO_2 emissions from power sector (ton/MWyr)

Type	Conversion	Emission factor
Renewable	Solar PV	0.14
	Wind	0.07
	Hydro (reservoir)	0.42
	Hydro (run-of-river)	0.16
	Geothermal	0.88
	Biomass	0.22
Fossil	Domestic coal	3.19
	Import coal	3.07
	Natural gas	3.04
Nuclear	once-through fuel cycle	0.57

The emission factors used in the model are based on the IPCC database used for the Global Energy Assessment Study of IIASA in Table 3.10 [60]. The impact of energy efficiency improvements are represented in SSP narratives which reduces the final energy consumed per production. The technological innovation for low carbon transition of energy demand both depends on social preferences reflecting the perceived costs and also temporal scale of their deployment affecting the spill-over effects to other regions in the world [106].

The demand for final energy sources are defined exogenously in the model using socio-economic parameters for SSPs and decomposition of CO_2 using Kaya Identity relation [180]. There is also a potential for climate mitigation using biomass which is defined with a maximum activity constraint of 13433 MWyr. This potential could be extended further with deployment of innovative technologies for fuel production in the transport and power sectors [184]. However this potential also has trade-off with food production, water usage and biodiversity protection as this strategy is based on extending the usage of limited biospheric resources.

The CO_2 emission pathways for Baseline scenario and climate targets represented by RCPs in SSP1 show same trend until 2030 with minor reductions for increasing climate ambition (Figure 3.52). This climate ambition is represented by increasing

Table 3.10: CO_2 emissions from final energy demand (ton/MWyr)

Final energy	Emission factor
Crude oil	2.31
Gasoline	2.19
Kerosene	2.25
Diesel oil	2.34
Fuel oil	2.44
LPG	1.99
Petrocoke	2.98
Coal	3.19
Natural gas	1.77
Biodiesel	1.72
Other biomass	3.15

penalty costs for CO_2 emissions which are internalized in the model in order to reduce emissions during the end of this century [83]. The difference between CO_2 emissions in Baseline scenario and RCPs represents the impact of using FITs from emission penalty costs for financing solar power plants complemented by wind power plants.

The CO_2 emissions depend on production activities which can be decomposed into population and GDP per capita multiplied by energy and carbon intensities of production (Equation 2.1). SSP1 narrative is represented with high increase in GDP per capita, low population growth, high improvement in energy efficiency and electrification favoring penetration of renewable energy sources. This results in the stabilization of CO_2 emission intensity with increasing renewable energy and reduction of increase in annual CO_2 emissions with energy efficiency improvements (Figure 3.53).

The pathways of CO_2 emissions are similar for Baseline scenario and climate ambition to RCP3.4 in SSP2 until 2050 (Figure 3.54). The trajectory of RCP2.6 separates from less ambitious climate targets and Baseline scenario in 2030 as a result of additional wind and solar power generation reaching 10 GW (Figure 3.33). The deviation of CO_2 emission trajectory in RCP2.6 is also the result of increase in total energy system cost reaching 24% compared to Baseline Scenario (Figure 3.5).

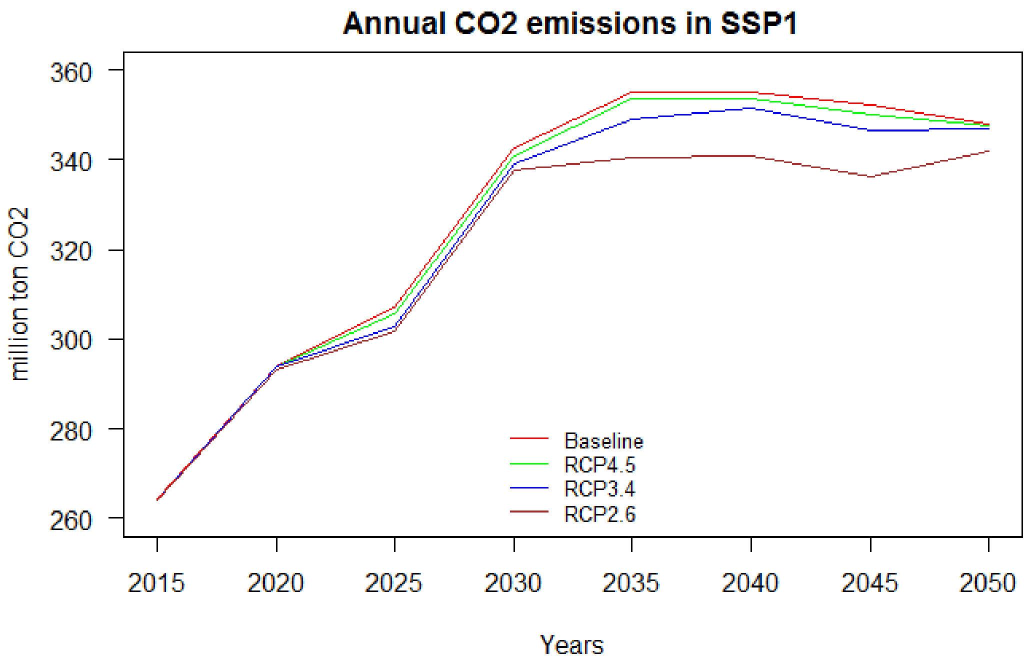

Figure 3.52: CO_2 emissions from energy sector in SSP1

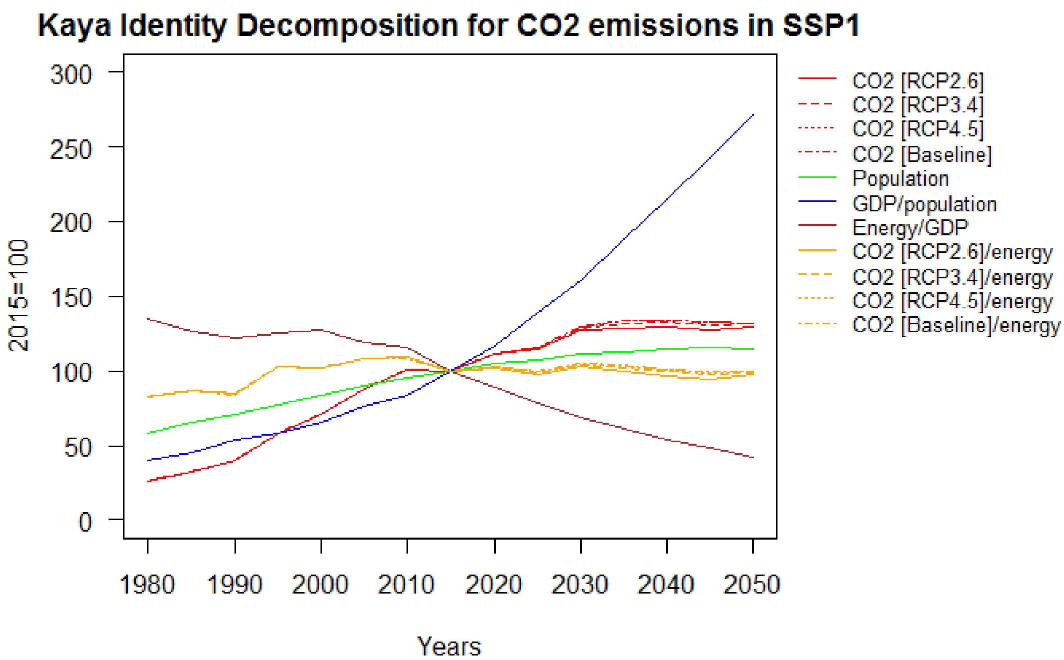

Figure 3.53: Kaya identity decomposition of CO_2 emissions in SSP1

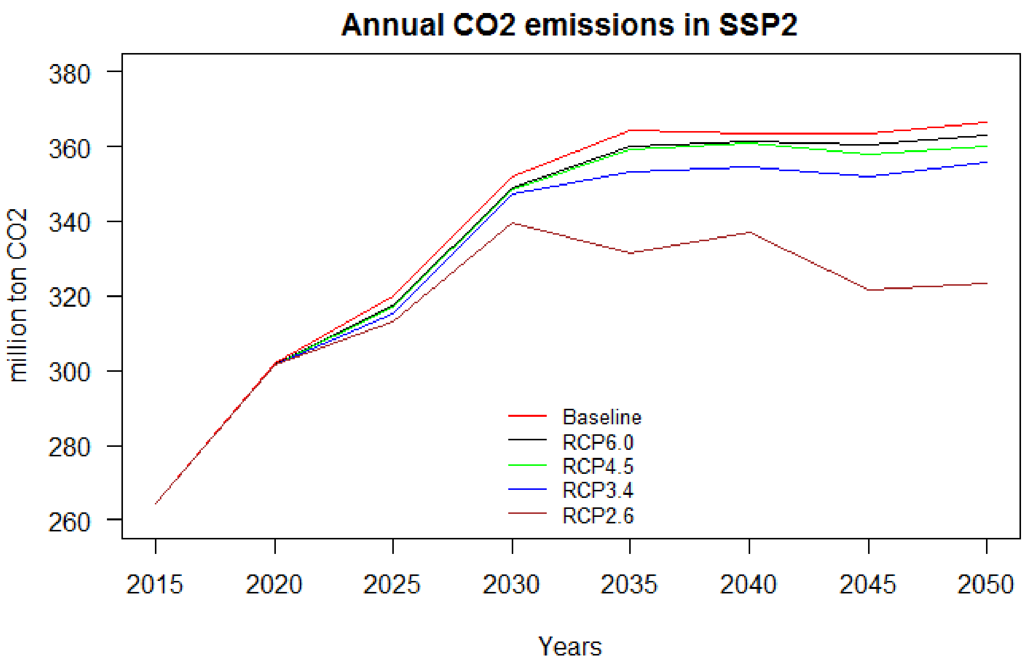

Figure 3.54: CO_2 emissions from energy sector in SSP2

The decomposition of CO_2 emissions using Kaya Identity method shows that increase in CO_2 intensity of production is compensated by decrease in energy intensity of production which stabilizes the total emissions after 2030 for all scenarios except the most stringent climate target of RCP2.6 (Figure 3.55). The carbon intensity of production decreases after 2030 in RCP2.6 resulting in deviation from less ambitious climate targets and Baseline scenario CO_2 emissions.

Annual CO_2 emissions from power sector follows a saturation pathway for Baseline scenario and RCP6.0 in SSP3 (Figure 3.56). The socio-economic assumptions for SSP3 is based on higher population growth and lower energy efficiency improvements compared to other SSPs resulting in higher final energy demand defined exogenously in the model. The pathways for more ambitious climate targets deviate with CO_2 emissions peaking in 2040 for RCP6.0 and in 2035 for RCP3.4 as a result of additional electricity generation from wind and solar power exceeding 10 GW in 2035 (Figure 3.33) and 20 GW in 2050 (Figure 3.33).

The saturation of CO_2 emission results from decrease in carbon intensity of pro-

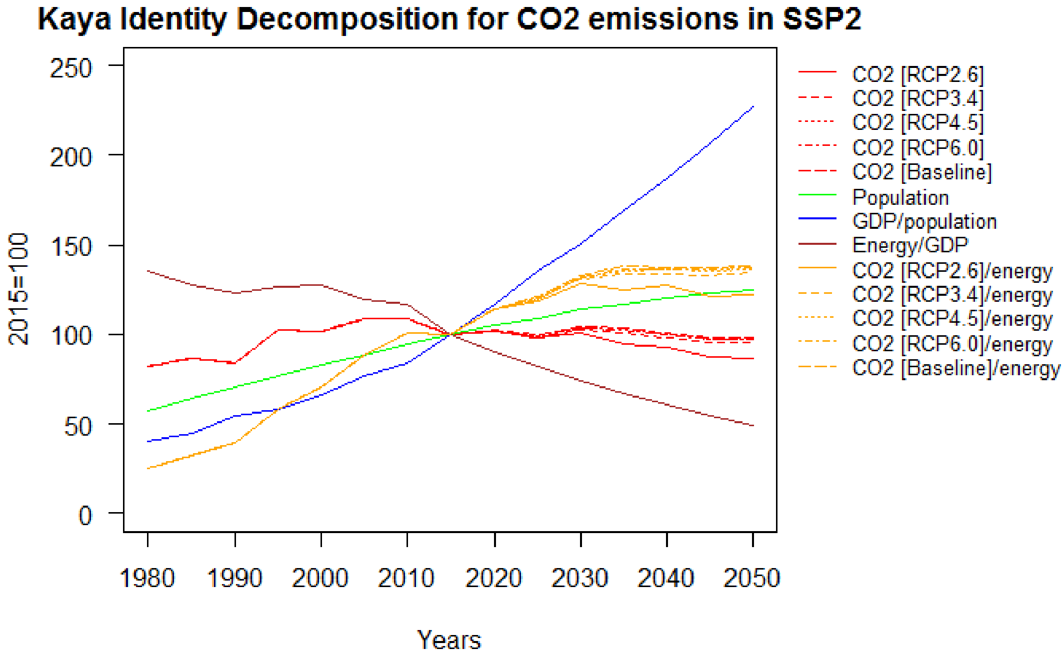

Figure 3.55: Kaya identity decomposition of CO_2 emissions in SSP2

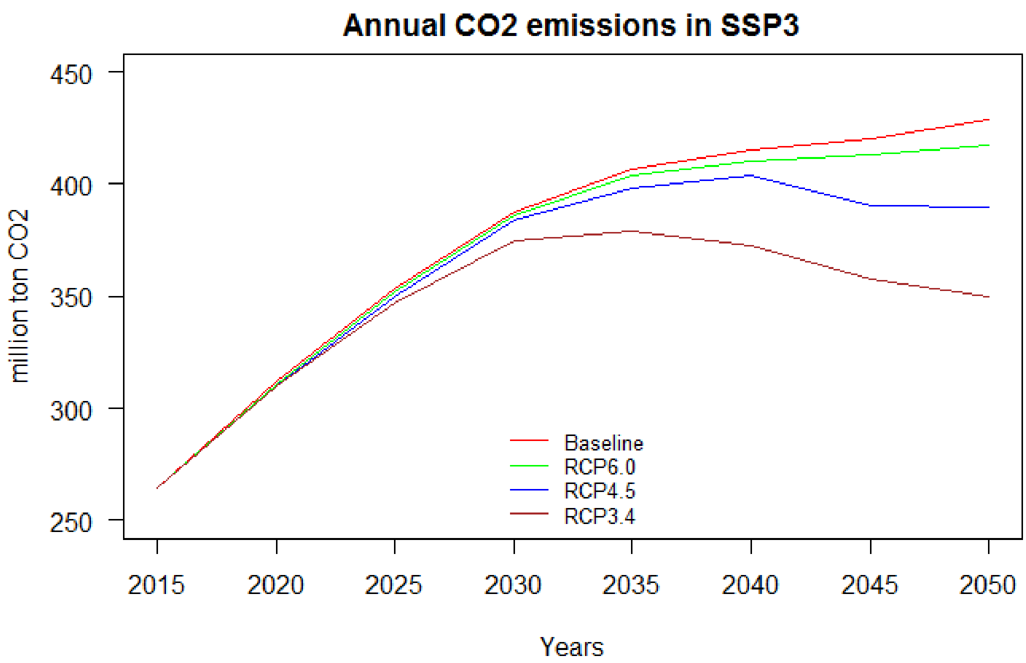

Figure 3.56: CO_2 emissions from energy sector in SSP3

duction for all scenarios and especially the most stringent scenario of RCP3.4 in SSP3 (Figure 3.57). Energy efficiency improvement follows the historical trajectory whereas increase in energy demand is driven by population growth exceeding the increase in productivity.

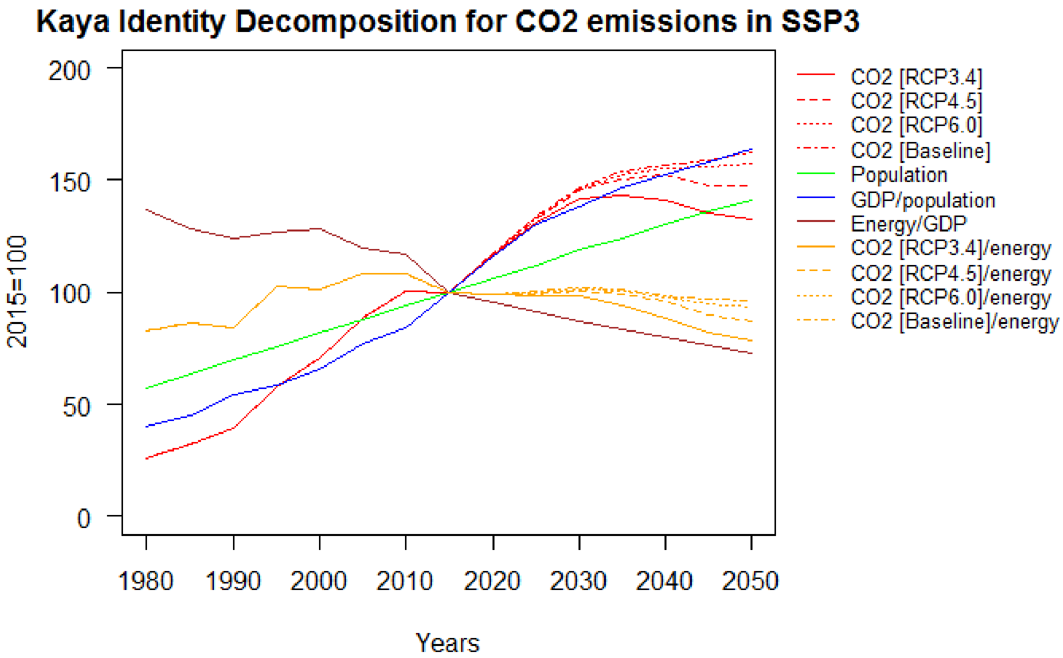

Figure 3.57: Kaya identity decomposition of CO_2 emissions in SSP3

These results show that CO_2 emission trajectories are highly dependent on initial assumptions based on SSPs and the usage of revenues from CO_2 emission penalties for FITs towards renewable energy. The climate mitigation strategy based on financing renewable energy technologies results in saturation of CO_2 emissions for the most stringent climate targets in SSPs with further reduction demanding for additional strategies on energy demand management.

Emissions of air pollutant SO_2 and NO_x emissions can be used as proxy for the usage of fossil fuel for electricity generation. SO_2 emissions are included as proxy for coal and oil power plants (Figure 2.12) and NO_x emissions for gas, coal and oil power plants (Figure 2.13). The SO_2 emission trajectory presents an increasing trend for both Baseline scenario and climate targets with RCPs in SSP1 (Figure 3.58). The availability of import coal for power generation results in increasing usage by the end of the modeling horizon despite efforts for penalty costs and filtering requirements defined in the model (Figure 3.7).

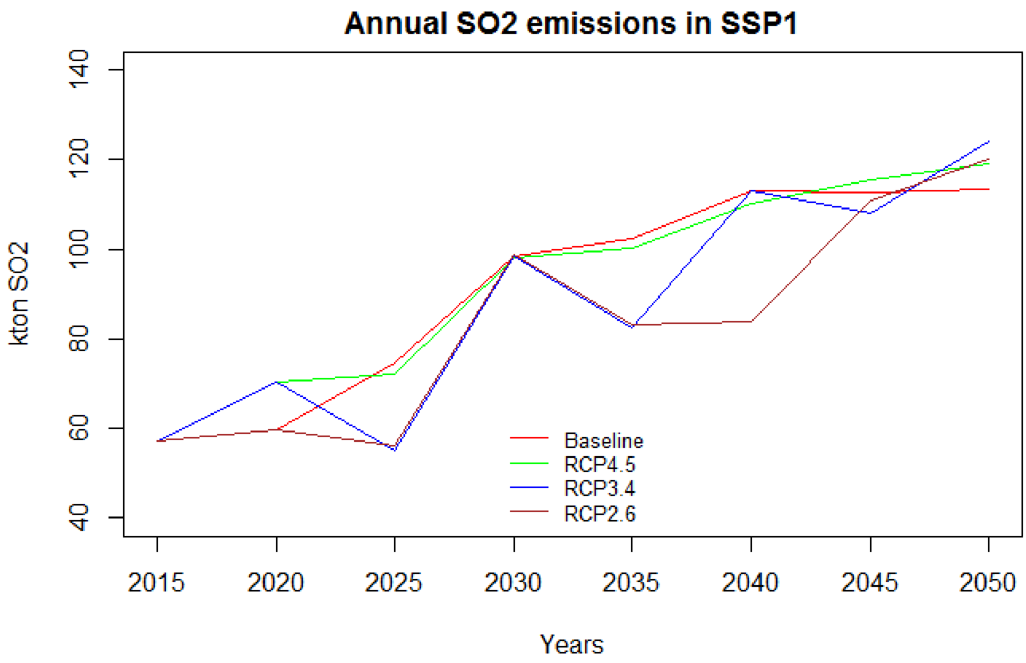

Figure 3.58: SO_2 emissions from power generation for RCPs in SSP1

NO_x emissions from power sector in SSP1 experience a peak in 2035 for Baseline scenario and climate targets of RCP4.5 and RCP2.6 despite the increasing usage of import coal for power generation (Figure 3.59). The main reason is the substitution of CCGT with NPPs for power generation as a result of high costs of import natural gas and also usage of installed natural gas pipelines for supplying the final energy demand (Figure 3.7).

SO_2 emissions from power sector in SSP1 increase from 60 kton in 2015 to approximately 120 kton in 2050 for Baseline scenario and climate targets of RCP6.0, RCP4.5 and RCP3.4 (Figure 3.60). The emissions for RCP2.6 reduce to as a result of reduced electricity generation from gas power plants by 10 GW between 2035 (Figure 3.34) and 2050 (Figure 3.39). The installed capacity of gas power plants is reduced to 6 GW with additional investment for wind and solar power plants reaching 120 GW in 2045 (Fig 3.15).

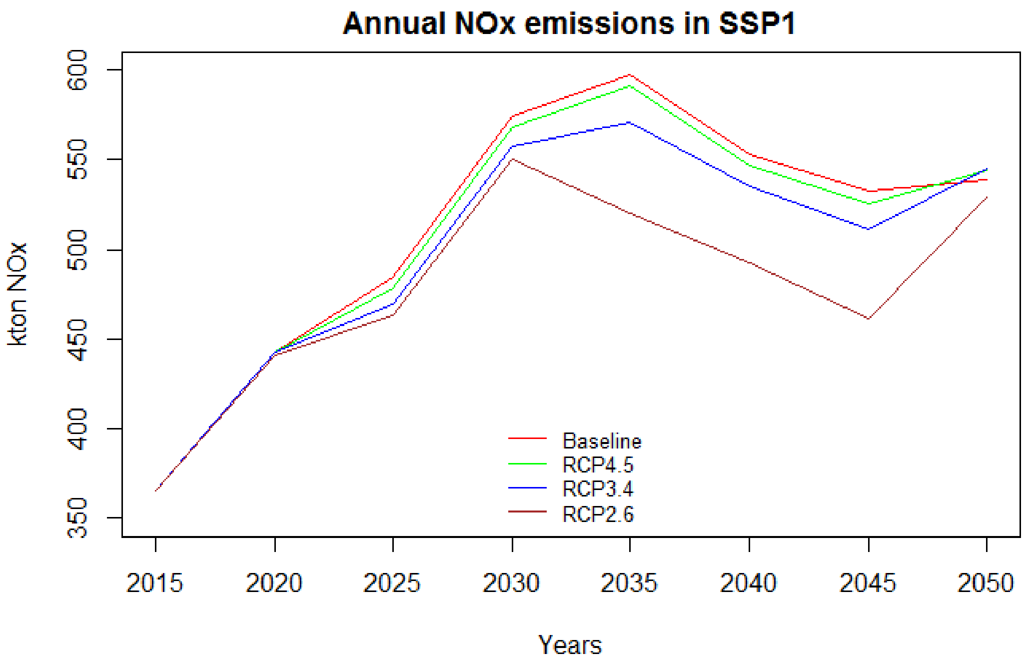

Figure 3.59: NO_x emissions from power generation for RCPs in SSP1

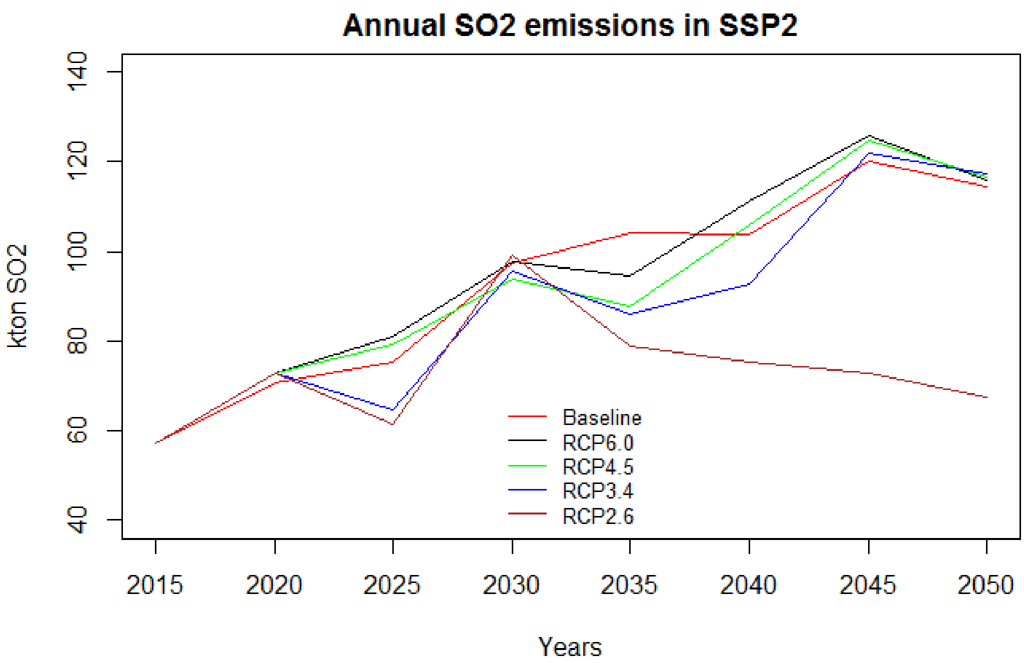

Figure 3.60: SO_2 emissions from power generation for RCPs in SSP2

The same affect of reduction from gas power plants for climate target of RCP2.6 in SSP2 can be seen in NO_x emissions in power sector decreasing from 500 kton in 2035 to approximately 300 kton in 2050 (Figure 3.61). The pathway for Baseline scenario and climate targets for RCP6.0, RCP4.5 and RCP3.4 deviates from RCP2.6 reaching 500 kton by 2050 as a result of higher power generation from gas power plants (Figure 3.38).

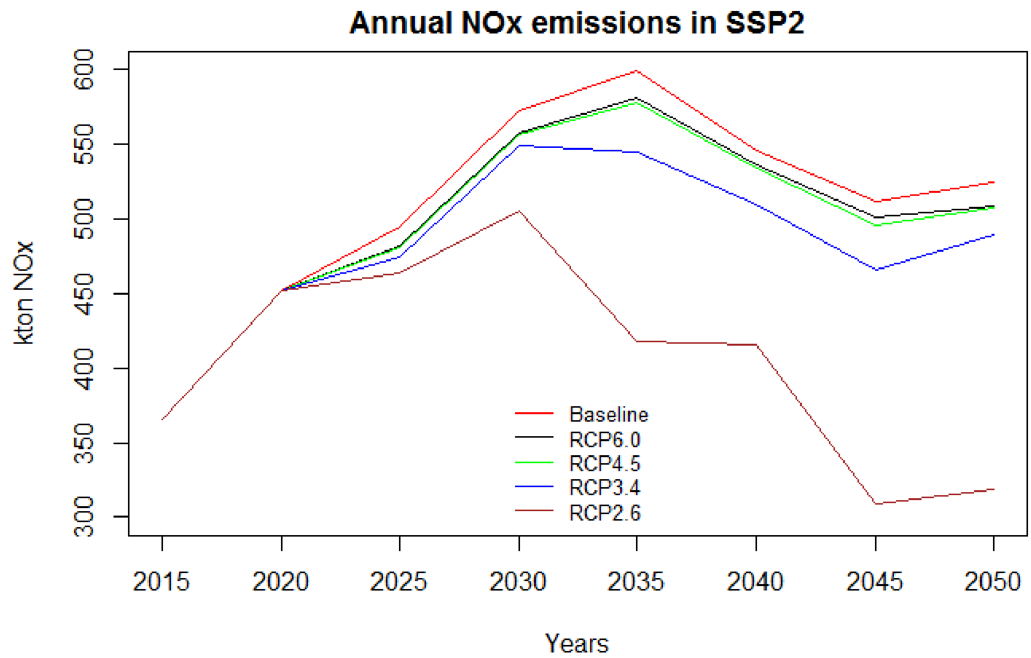

Figure 3.61: NO_x emissions from power generation for RCPs in SSP2

SO_2 emissions from power sector follow increasing trajectory for Baseline scenario and climate target of RCP6.0 increasing from 60 kton in 2035 to 120 kton in 2050 followed by a saturation pathway for RCP4.5 at 80 kton and a decreasing pathway for RCP3.4 from 80 kton in 2030 to 20 kton in 2050 (Figure 3.62). Substitution is between gas and domestic coal power plants in RCP4.5 with additional wind and solar power plants reaching 120 GW in 2050 (Figure 3.18). The most stringent climate target of RCP3.4 in SSP3 includes additional domestic coal power plants for substitution with additional wind and solar power plants reaching 150 GW in 2050 (Figure 3.19).

The trajectories for NO_x emissions in SSP3 are determined by power generation

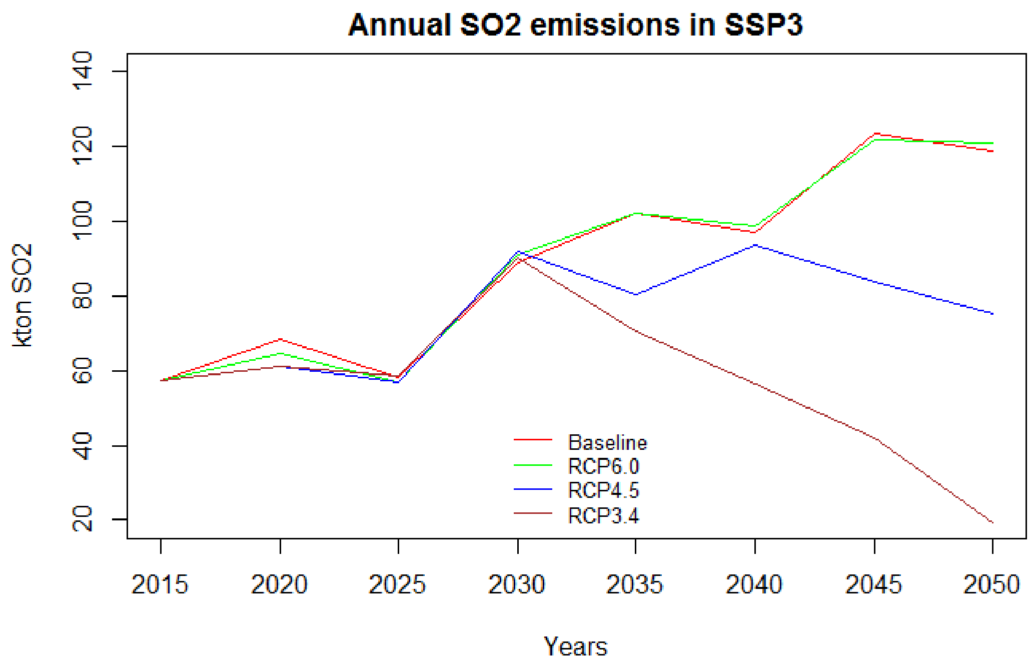

Figure 3.62: SO_2 emissions from power generation for RCPs in SSP3

from gas power plants (Figure 3.63). The installed capacity of gas power plants are reduced to 6 GW for RCP3.4 (Figure 3.48) increasing to 6.6 GW for RCP 4.5 (Figure 3.47) and to 12 GW for RCP6.0 (Figure 3.46). The differences in trajectories are further contributed by phase-out for investment in oil power plants with increasing CO_2 emission penalty costs in RCP3.4 (Figure 3.19).

The general assumptions for applying penalty costs to air pollutant emissions and availability of filtering technologies to prevent paying these penalty costs are insufficient to reduce emissions of SO_2 and NO_x emissions for all scenarios in SSP1. This results from lower cost of coal as primary energy supply increasing their usage and the existing capacity of gas pipelines and power plants creating a carbon lock-in in the energy system. The increasing revenues collected from CO_2 emissions penalty costs increases the penetration of wind and solar power for the most stringent climate scenarios in SSP2 and SSP3 creating an opportunity also for the reduction of air pollutant emissions.

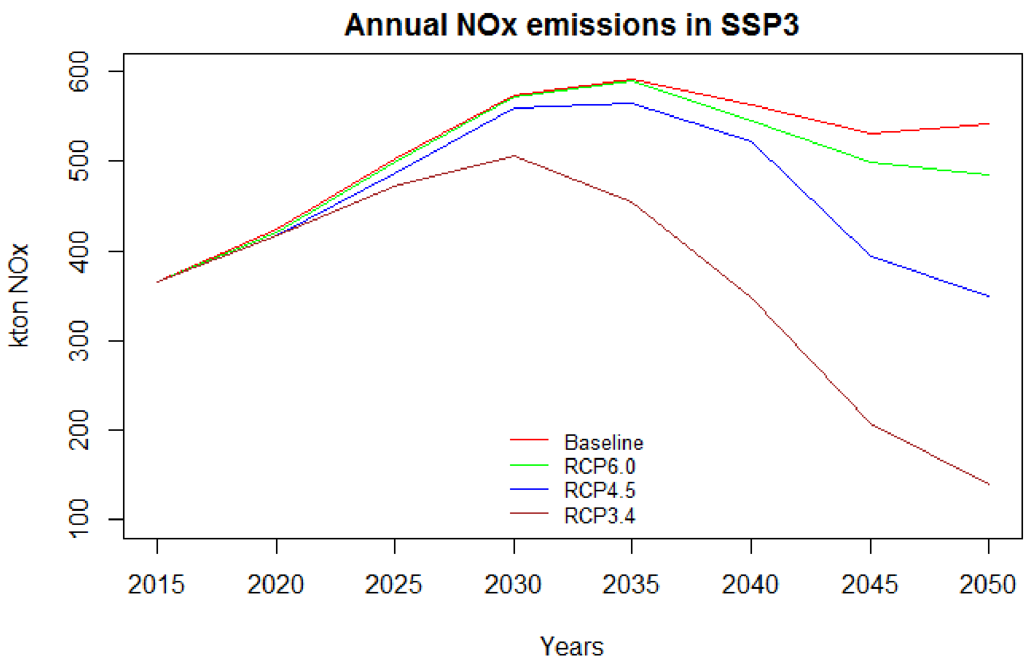

Figure 3.63: NO_x emissions from power generation for RCPs in SSP3

3.1.6 Nuclear fuel cycle costs

The life cycle of nuclear power generation starts with the mining and milling of uranium ores in the front end of the nuclear fuel cycle followed by spent fuel storage for reprocessing and finally for disposal (Figure 3.64) [175]. The transfer of sensitive fuel enrichment and reprocessing technologies are subject to safeguards according to international agreements controlled by the guidelines of the Nuclear Suppliers Group [132]. Although Turkey is a member to this group, the fuel cycle agreements are included as responsibilities of vendor countries and Turkey has not yet made any agreements for nuclear fuel production or spent fuel reprocessing [133].

Energy modeling studies in general include NPPs similar to conventional power plants whereas the nuclear fuel cycle provides opportunities for further usage after enrichment. Even for the case for once-through nuclear fuel cycle, the low fuel costs and low amounts of spent fuel and waste generation compared to fossil power plants geographically more uniform availability of uranium ores favors investment for NPPs [173]. The equations for mass flow calculation for open fuel cycle with one unit of

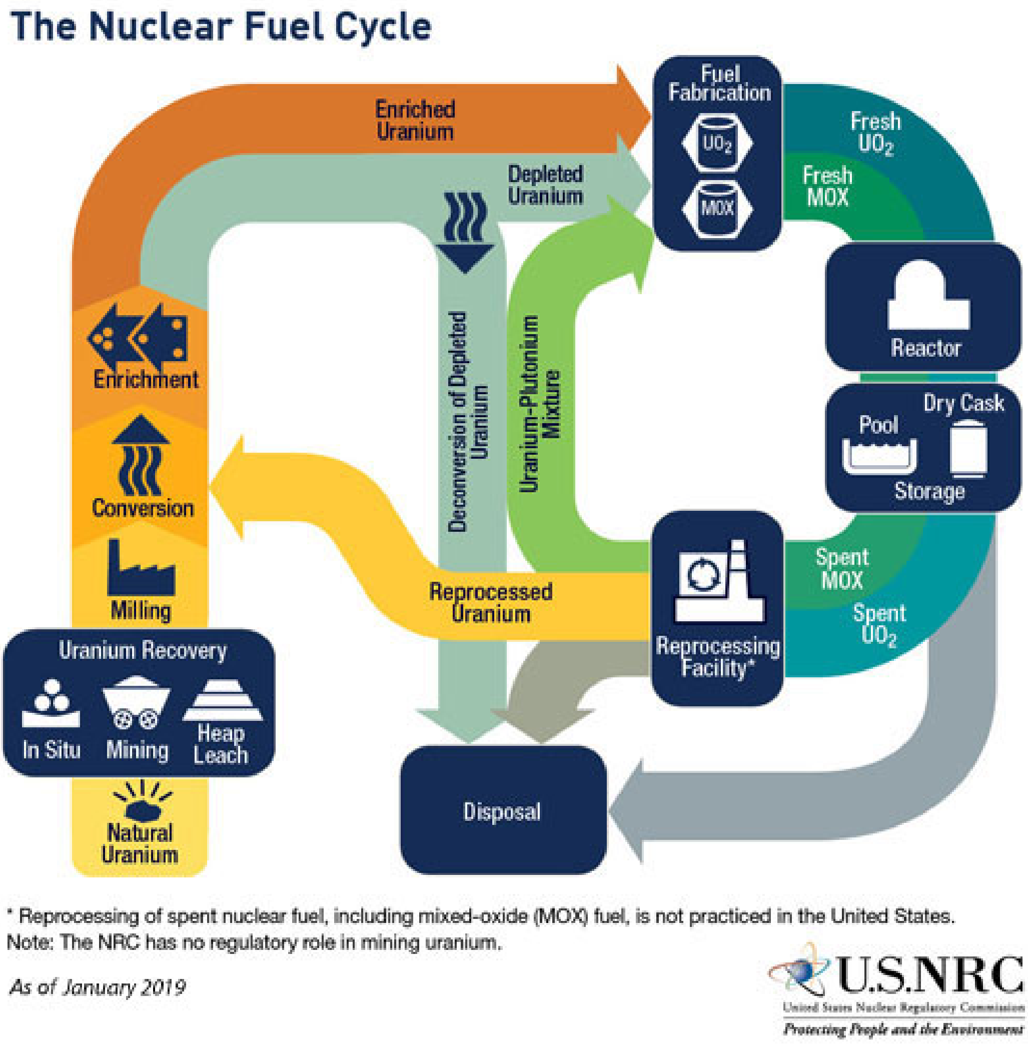

Figure 3.64: Complete nuclear fuel life-cycle

advanced NPP in MESSAGE user's guide are used in the model with annual requirements listed in Table 3.11 [77].

Table 3.11: Annual output for 1 GW NPP reactor unit

Output	Unit	Value
Fresh fuel	tHM	17.89
Fuel in core	tHM	71.93
Natural uranium	tHM	166.25
Conversion	tHM	166.25
Seperative work unit	tSWU	125.19
Depleted uranium	tHM	148.36
Spent fuel discharges	tHM	17.89

The cost of nuclear fuel cycle in SSP1 reaches 1.2 billion US$ as a result of 5 GW NPP commissioned in 2040 increasing to 9 GW in 2045 and 11 GW in 2050 (Figure 3.65). The modeling horizon is limited to 2050 causing the remaining operating lifetime of 50 years for NPPs commissioned in 2040 causing end-of-horizon effect (Equation 3.1). The increase in installed capacity causes high costs of spent fuel storage by 2050 which would dominate in the period after 2050.

The main assumption for back-end of the nuclear fuel cycle is the retaining of spent fuel removed from reactor core for 5 years in cooling pools. Spent fuel is stored in cooling pools both for removing decay heat and also for maintaining the reactor radial power profile as the burn-up of fuel in the center is higher than the circumference of the core due to neutron leakage [102]. The amount of spent fuel storage increases to approximately 370 tHM in 2040 to 1870 tHM in 2050 (Figure 3.66).

The cost of nuclear fuel cycle is reduced by approximately 500 million US$ for RCP4.5 in SSP1 as a result of reduction in NPP installed capacity to 7 GW in 2045 and 8 GW in 2050 (Figure 3.67). The reduction in installed NPP units also results in cumulative reduction in back-end of the nuclear fuel cycle with reduced costs of spent fuel storage.

The spent fuel storage for RCP4.5 in SSP1 reduces by 100 tHM as a result of reduction in NPP installed capacity (Figure 3.68). The reduction of spent fuel storage

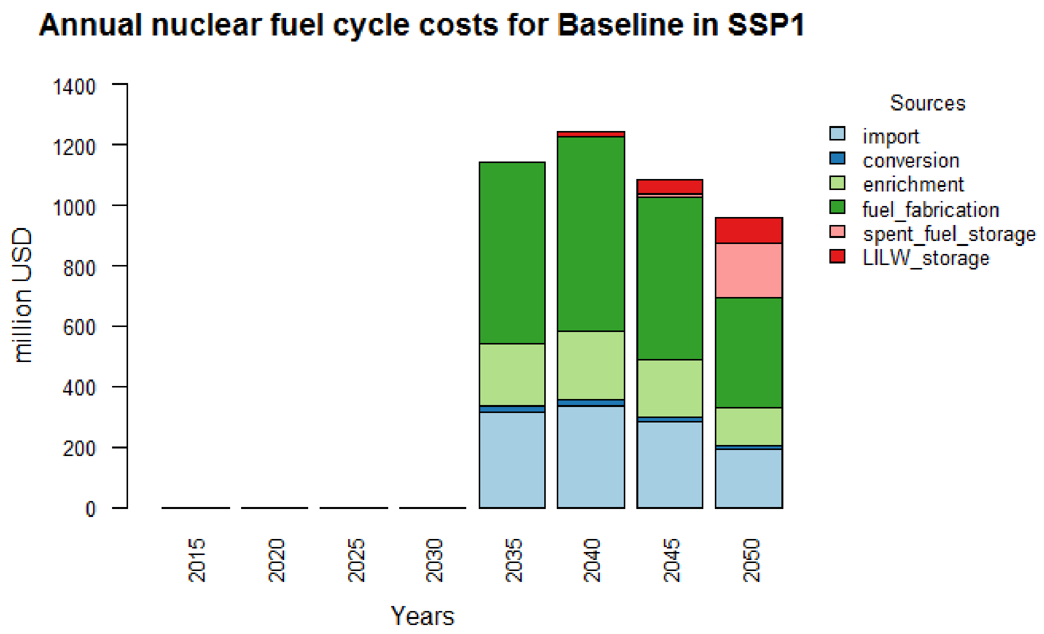

Figure 3.65: Annual nuclear fuel cycle cost in SSP1 for Baseline

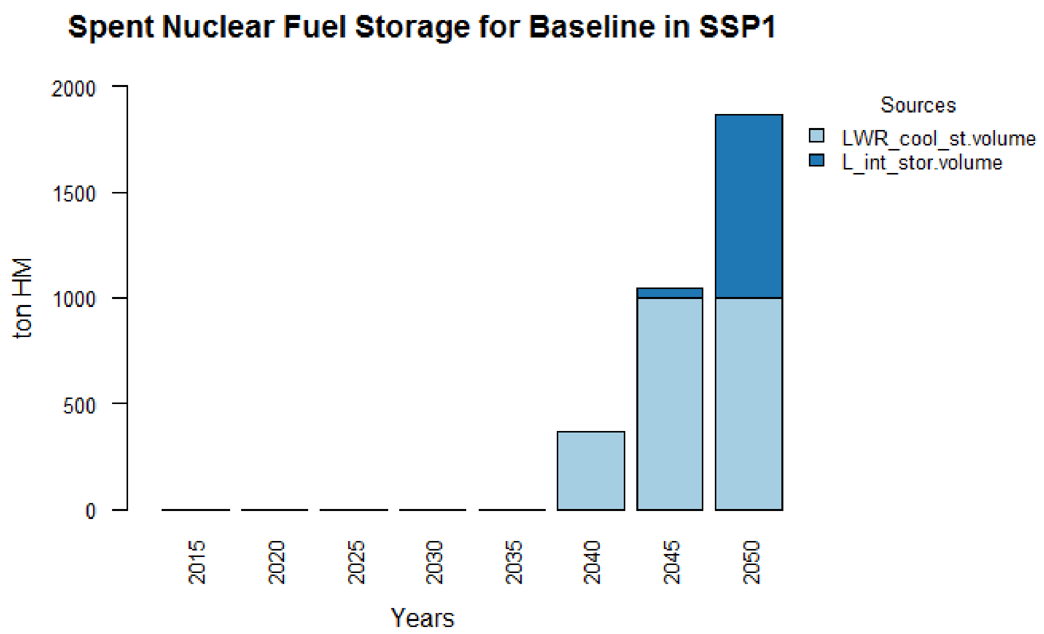

Figure 3.66: Spent nuclear fuel storage in SSP1 for Baseline

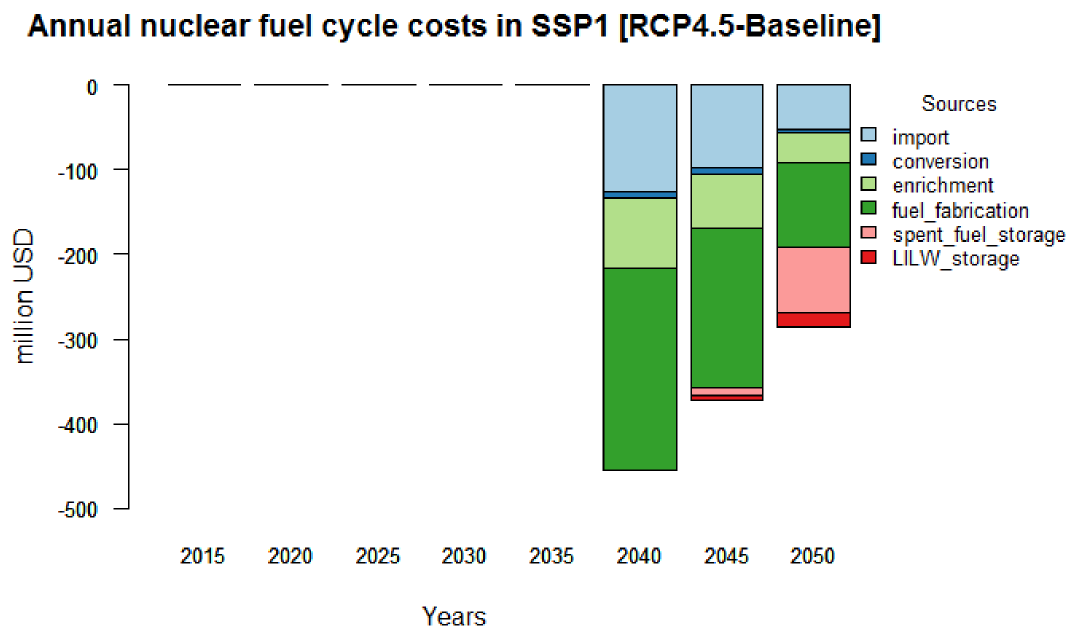

Figure 3.67: Annual nuclear fuel cycle cost difference in SSP1 for RCP4.5

reaches 400 tHM in 2050 reducing the storage costs.

Fuel cycle costs for RCP3.4 in SSP1 are reduced by 1 billion US$ in 2040 as a result of reduction of NPP installed capacity to 4 GW in 2040 and 5 GW in 2050 (Figure 3.69). Electricity generation from NPPs is substituted by additional wind and solar power plants reaching 30 GW by the end of the modeling horizon (Figure 3.9).

Spent fuel cooling storage capacity reaches 957 tHM in 2050 for RCP3.4 in SSP1 which is below the storage capacity upper volume of 1000 tHM (Figure 3.70). The slow-down of NPP investments after 2040 results in reduction of nuclear fuel requirements as fresh fuel loading is lower than initial core loading to nuclear reactors (Table 3.11).

NPP installed capacity in SSP2 increases from 1 GW in 2035 to 13 GW in 2050 for Baseline scenario with nuclear fuel cycle costs reaching 1.5 billion US$ in 2040 and reducing to 1.2 billion US$ by the end of the modeling horizon (Figure 3.71). The reduction in front-end nuclear fuel cycle costs are compensated by increasing spent fuel storage costs reaching 265 million US$ by 2050. The operating lifetime of NPPs

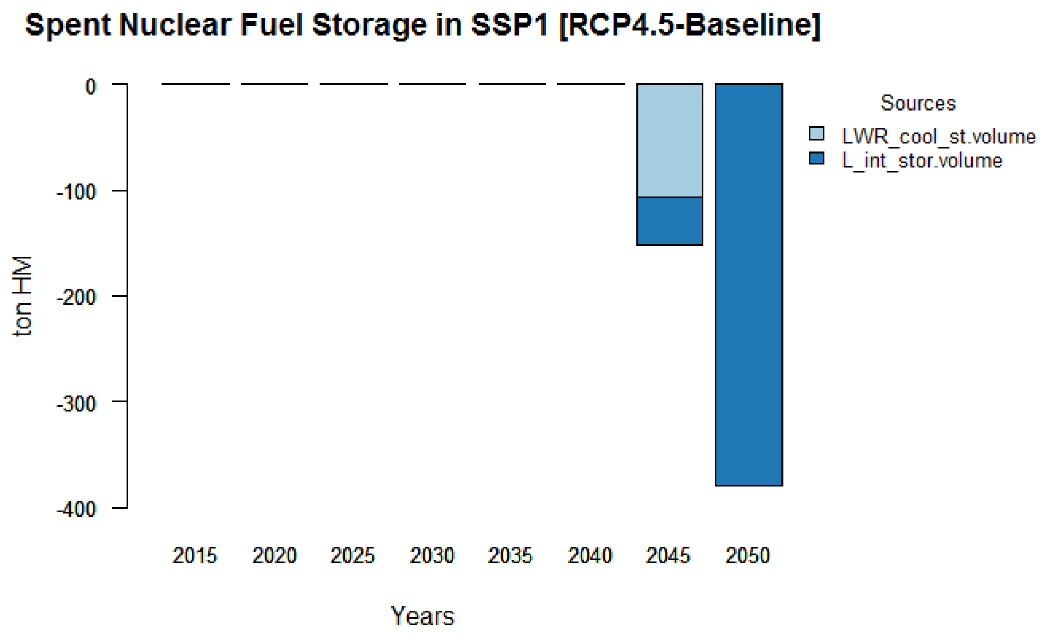

Figure 3.68: Spent nuclear fuel storage difference in SSP1 for RCP4.5

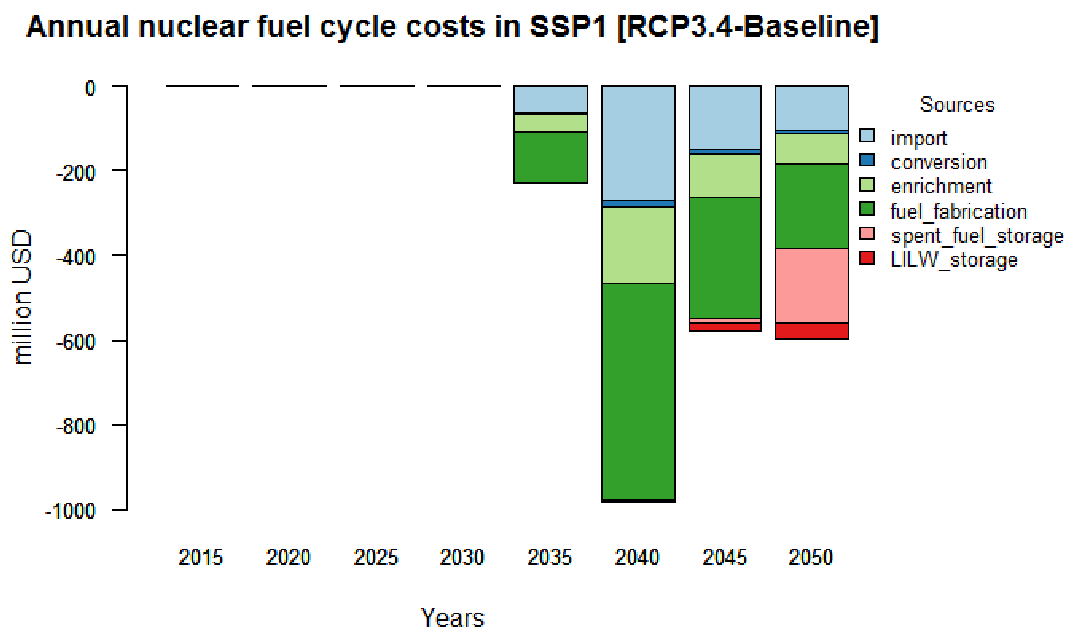

Figure 3.69: Annual nuclear fuel cycle cost difference in SSP1 for RCP3.4

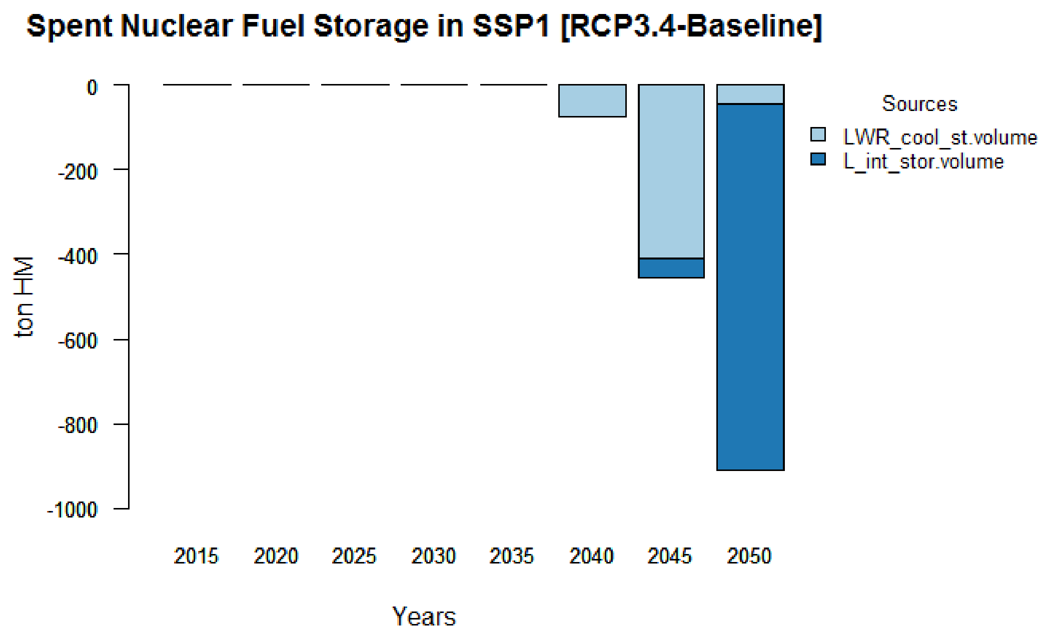

Figure 3.70: Spent nuclear fuel storage difference in SSP1 for RCP3.4

installed in 2035 exceeds the modeling horizon by 45 years which would result in accumulation of spent fuel storage costs requiring early disposal.

The spent fuel cooling storage volume of 1000 tHM is consumed by 2045 which acts as a constraint for additional NPP investments (Figure 3.72). This constraint is strengthened with the required retention time of 5 years for spent fuel to be transferred to interim storage for disposal. The cumulative costs of spent fuel interim storage provide additional constraint for cost optimization which would come in affect by the end of the operating lifetimes of NPPs. The amount of spent fuel storage reaches 2300 tHM in total which could create an opportunity for localization of nuclear fuel cycle services.

The installed capacity of NPPs for RCP6.0 in SSP2 is reduced by 1 GW providing temporal difference in nuclear fuel cycle costs (Figure 3.73). The role of nuclear power for climate target of RCP6.0 is smaller compared to Baseline scenario as the availability of FITs from revenues of CO_2 emission penalty costs provides additional investment of wind and solar power plants exceeding 15 GW by 2045 (Figure 3.12).

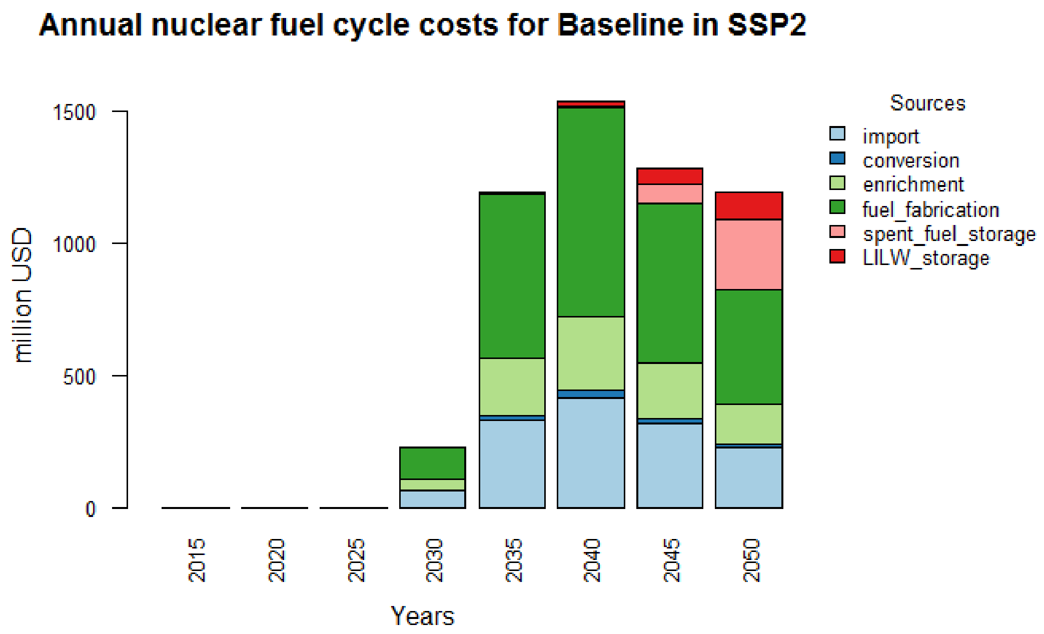

Figure 3.71: Annual nuclear fuel cycle cost in SSP2 for Baseline

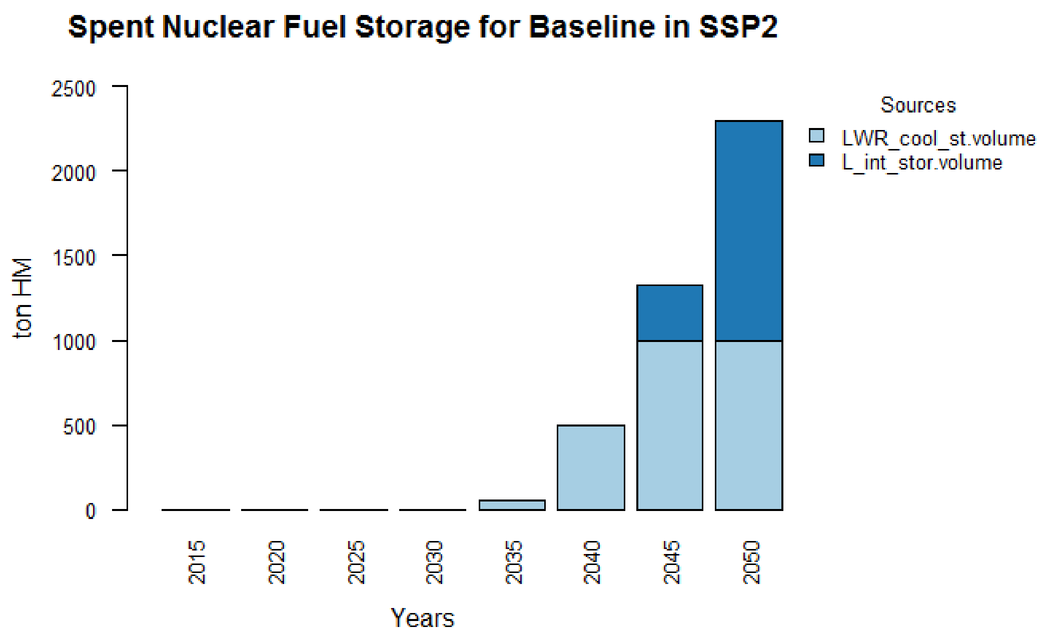

Figure 3.72: Spent nuclear fuel storage storage in SSP2

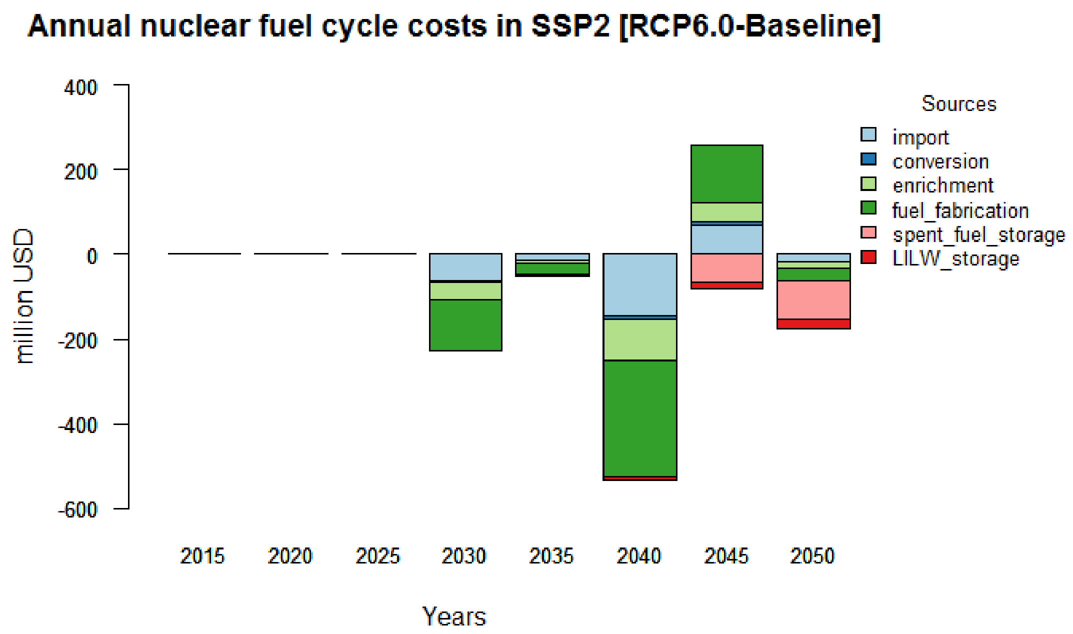

Figure 3.73: Annual nuclear fuel cycle cost difference in SSP2 for RCP6.0

The amount of spent fuel storage is reduced to 1850 tHM for RCP6.0 in SSP2 as a result of additional wind and solar power substituting NPPs for low carbon transition of the energy sector (Figure 3.74). The capacity of 1000 tHM for spent fuel cooling storage is completed in 2050 which would result in increasing spent fuel stored for disposal after the end of the modeling horizon.

The role of nuclear power for RCP4.5 in SSP2 is selected as a transition technology for low carbon energy supply system as a complementrary to intermittent solar and wind power after 2040 (Figure 3.75). The installed capacity of NPPs are stabilized at 5 GW after 2040 with additional requirement for low carbon power generation from wind and solar power exceeding 40 GW by the end of the modeling horizon (Figure 3.13).

The amount of spent fuel storage is reduced to 1090 tHM for RCP4.5 in SSP2 as a result of additional wind and solar power substituting NPPs for low carbon transition of the energy sector (Figure 3.76). The back-end nuclear fuel cycle includes mainly spent fuel cooling requirements whereas interim storage costs are outside the

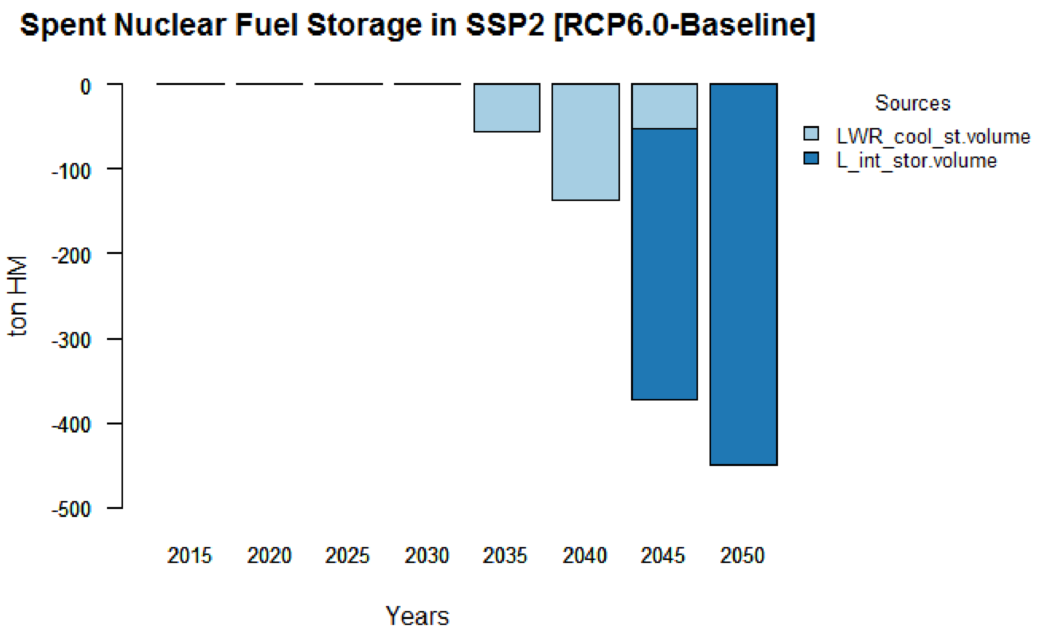

Figure 3.74: Spent nuclear fuel storage difference in SSP2 for RCP6.0

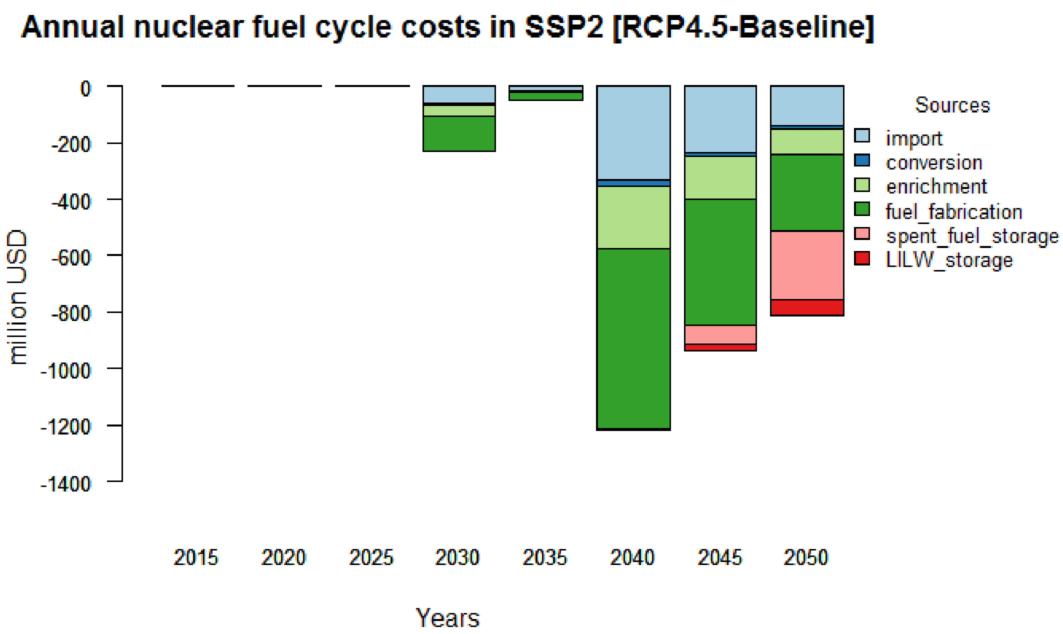

Figure 3.75: Annual nuclear fuel cycle cost difference in SSP2 for RCP4.5

modeling horizon which would make nuclear energy less cost effective compared to renewable energy technologies for low carbon transition of the power sector.

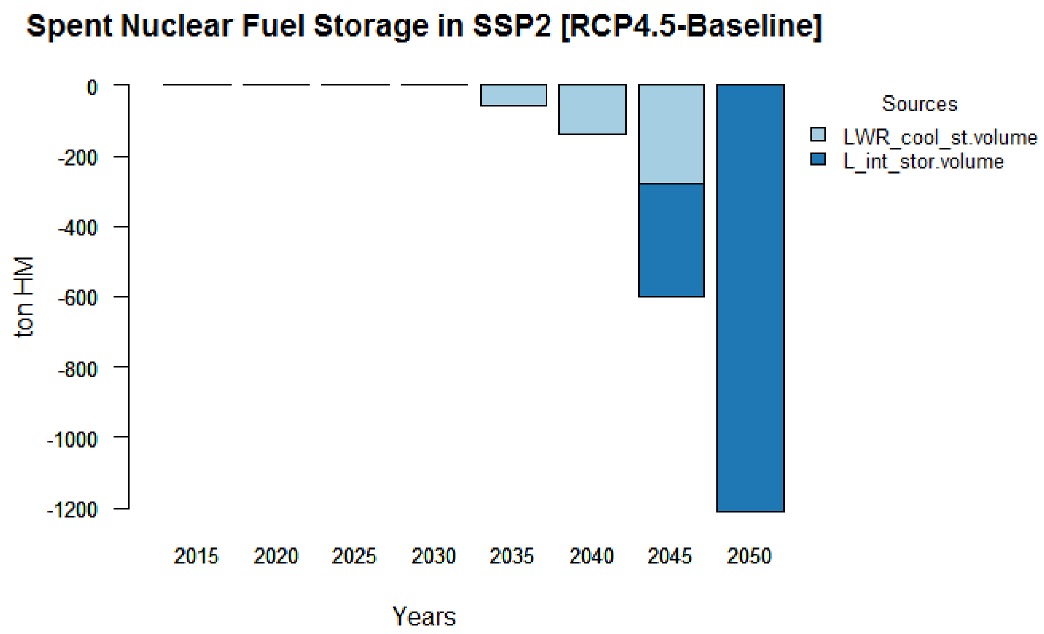

Figure 3.76: Spent nuclear fuel storage difference in SSP2 for RCP4.5

The role of nuclear power is reduced to marginal power supply for RCP3.4 in SSP2 as a result of increasing revenues from CO_2 emission penalties for subsidizing additional wind and solar power plants (Figure 3.77). The cost of nuclear fuel cycle reaches 456 million US$ in 2035 for initial core loading of 2 GW installed NPP followed by annual costs in the range of 120 million US$ annually for fresh fuel loading to reactor core.

The capacity used for spent fuel cooling and interim storage are reduced to 407 tHM which is less than 1000 tHM capacity causing the extended storage of spent fuel in cooling ponds to reduce back-end nuclear fuel cycle costs (Figure 3.78). The future of nuclear power after the modeling horizon would include additional costs of spent fuel storage for disposal which would affect the economics of power generation from NPPs negatively.

The costs of nuclear fuel cycle for RCP2.6 in SSP2 start from 2025 for the initial

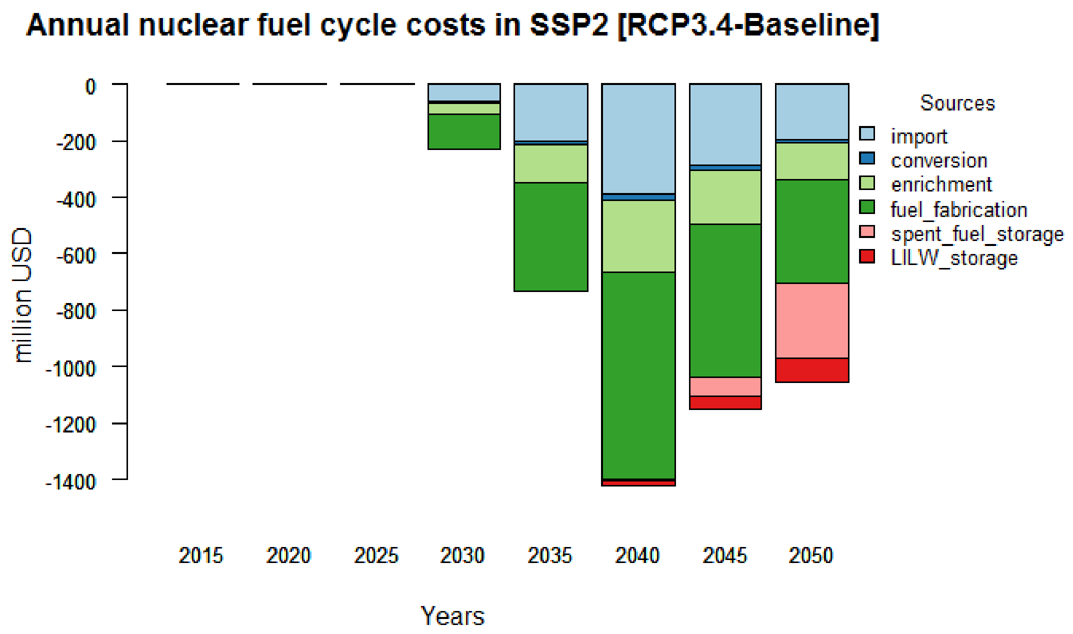

Figure 3.77: Annual nuclear fuel cycle cost difference in SSP2 for RCP3.4

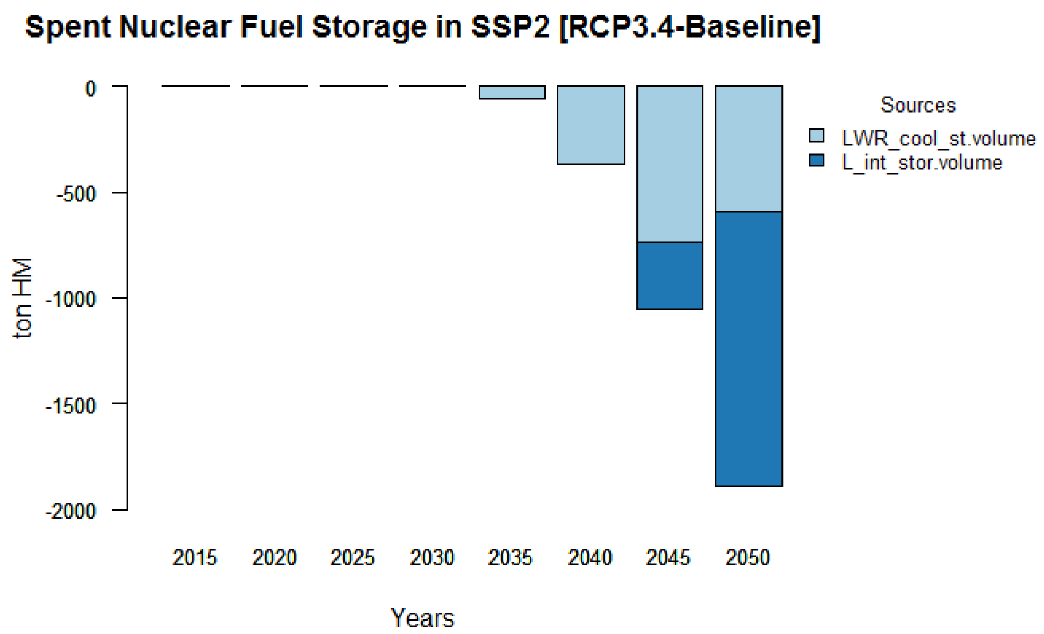

Figure 3.78: Spent nuclear fuel storage difference in SSP2 for RCP3.4

core loading of 1 GW NPP installed in NPP (Figure 3.79). Further installation of NPPs are prevented by increasing subsidy to wind and solar power plants as a result of increasing revenues from CO_2 emission penalty costs. Nuclear fuel cycle cost initially amounts to 228 million US$ in 2025 reducing the 50 million US$ annually for fresh fuel loading in reactor core.

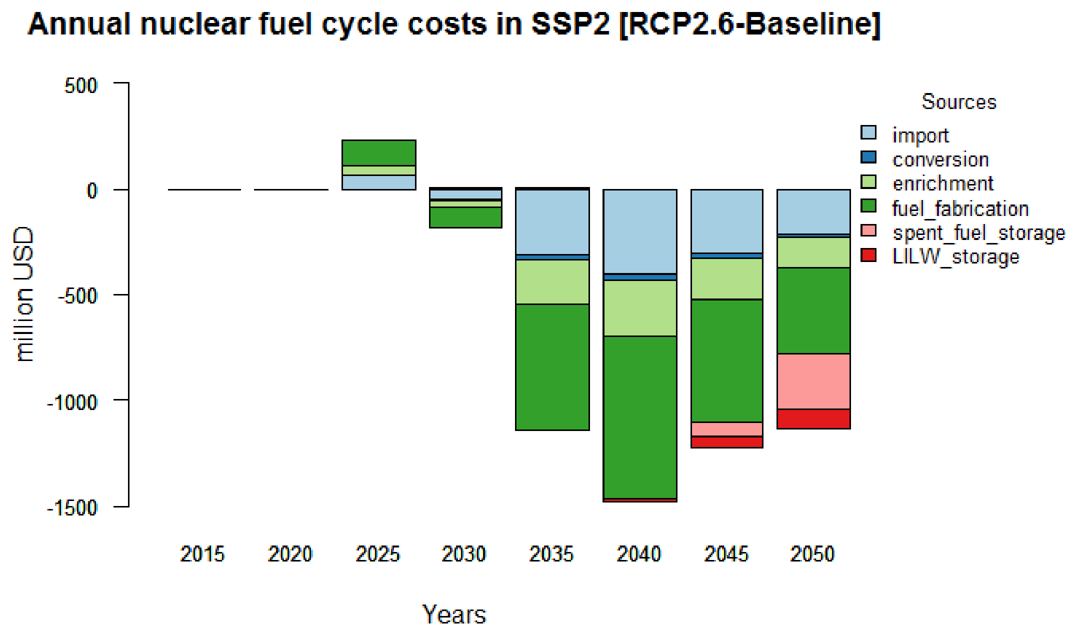

Figure 3.79: Annual nuclear fuel cycle cost difference in SSP2 for RCP2.6

The requirements for spent nuclear fuel storage are minimum for RCP2.6 in SSP2 with total amount reaching 275 tHM in spent fuel cooling storage pools (Figure 3.80). The remaining capacity of spent fuel cooling defined in the model is 725 tHM which could provide an opportunity for extended usage of 1 GW NPP after the modeling horizon.

The costs of nuclear fuel cycle for Baseline scenario in SSP3 are considerably higher than SSP2 and SSP1 as NPPs are utilized for supplying increasing base load electricity demand (Figure 3.81). The installed capacities of NPPs reaches 4 GW in 2020 followed by increase to 5 GW in 2025, 8 GW in 2035 and stabilizing at 13 GW after 2040. The initial core loading requirement reaches 1 billion US$ in 2015 for 4 GW NPP and reaching 1.15 in 2030 with addional initial core loading of 3 GW and fresh

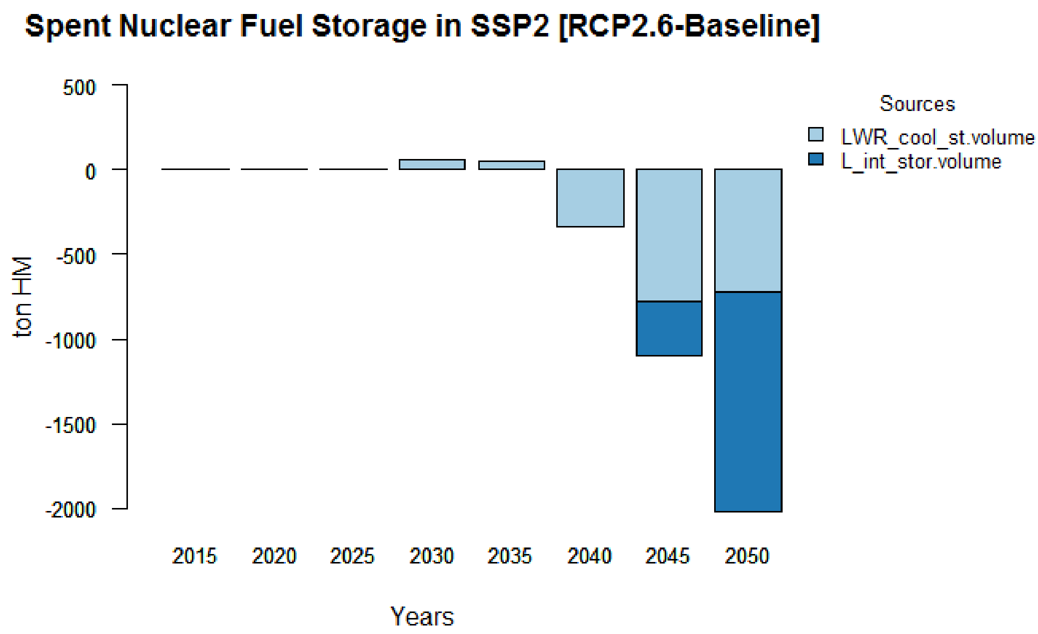

Figure 3.80: Spent nuclear fuel storage difference in SSP2 for RCP2.6

fuel loading of 5 GW NPP. The cost of fresh fuel loading stabilizes below 1 billion US$ after 2040 leaving the remaining cost to storage of spent fuel for cooling and disposal. Early deployment of NPPs causes larger storage of LILW with cost reaching 200 million US$ annually by the end of the modeling horizon.

The capacity of spent fuel storage cooling is used completely by 2030 increasing the back-end nuclear fuel cycle cost after this period as a result of higher cost of spent fuel storage for disposal (Figure 3.82). The amount of spent fuel storage for cooling and disposal reaches 4540 tHM by the end of the modeling horizon which would require a disposal program for a large fleet of NPPs.

The nuclear fuel cycle costs for RCP6.0 in SSP3 experiences reductions for initial core loading of NPPs as a result of stabilization of installed capacity to 4 GW until 2035 and increasing to 9 GW in 2040 and 10 GW in 2050 (Figure 3.83). Together with reduction in costs of back-end nuclear fuel cycle the reduction of nuclear fuel cycle costs exceeds 400 million US$ compared to Baseline scenario.

The amount of spent fuel storage reduces to 3260 tHM by the end of the modeling

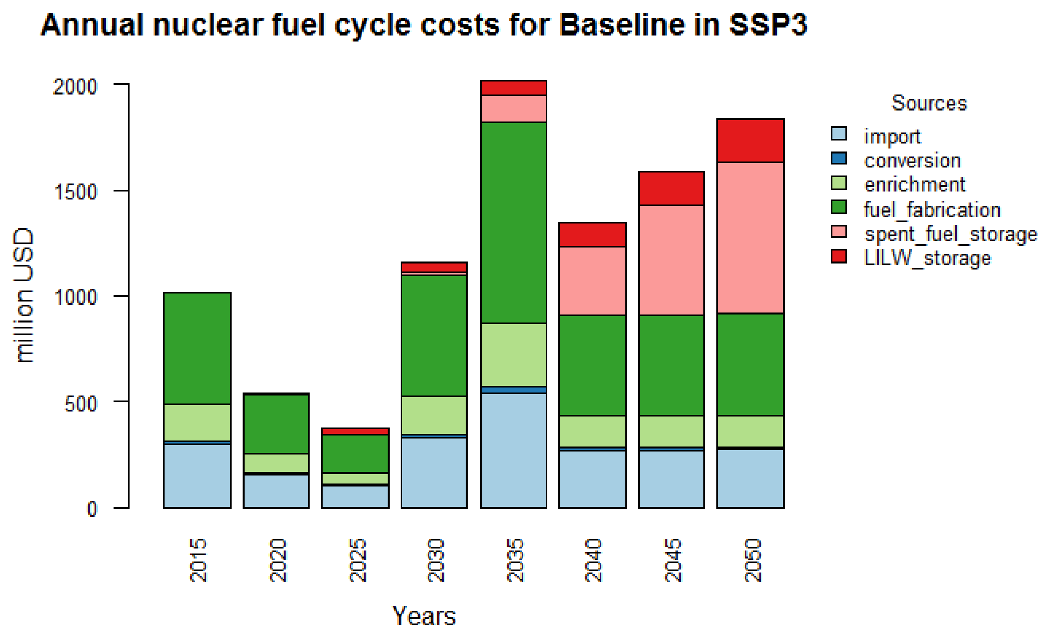

Figure 3.81: Annual nuclear fuel cycle cost in SSP3 for Baseline

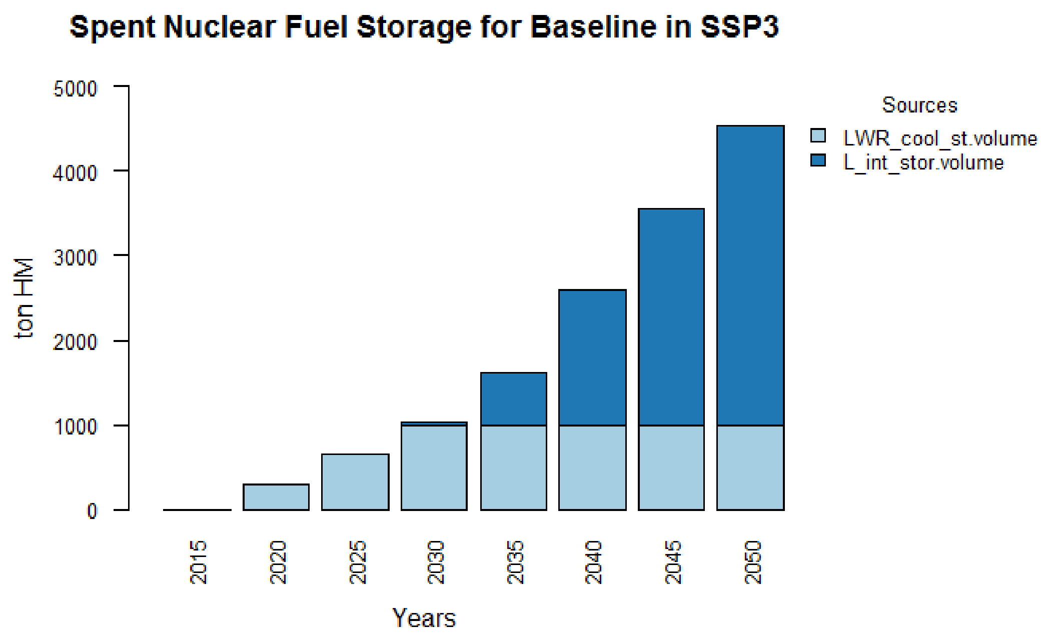

Figure 3.82: Spent nuclear fuel storage in SSP3 for Baseline

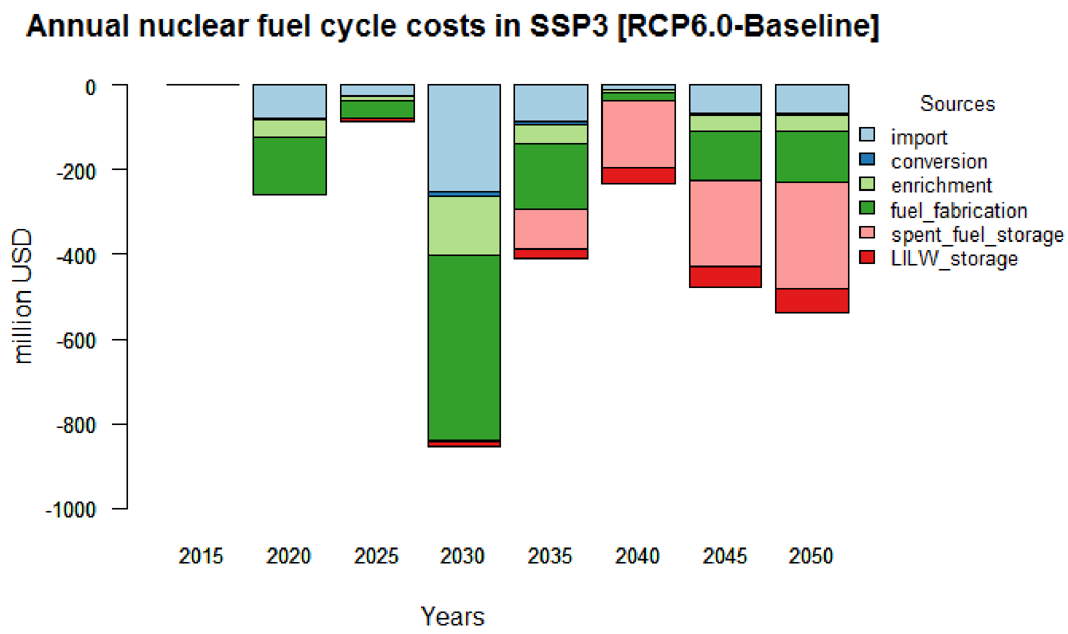

Figure 3.83: Annual nuclear fuel cycle cost difference in SSP3 for RCP6.0

horizon as a result of reduction of installed NPP capacity due to higher penetration of wind and solar power generation for low carbon transition for RCP6.0 in SSP3 (Figure 3.84). The capacity of spent fuel storage for cooling reaches 1000 tHM in 2035 causing increasing costs of back-end nuclear fuel cycle as the amount of spent fuel stored for disposal increases to 2260 tHM.

The nuclear fuel cycle cost for RCP4.5 in SSP3 is reduced to 1 billion US$ in 2015 for initial core loading of 4 GW NPP followed by reduction to 287 million US$ annually after 2020 for fresh fuel loading in nuclear reactor core (Figure 3.85). The back-end nuclear fuel cycle costs reduces linearly to 286 million US$ by the end of the modeling horizon due to reduced requirements for initial core loading of NPPs.

The amount of spent fuel storage for cooling reaches 1000 tHM in 2035 as a result of early deployment of 4 GW NPPs for RCP4.5 in SSP3 (Figure 3.86). The total amount of spent fuel storage for cooling and disposal reaches 1965 tHM by the end of the modeling horizon which is considerably reduced from 4540 tHM in Baseline scenario.

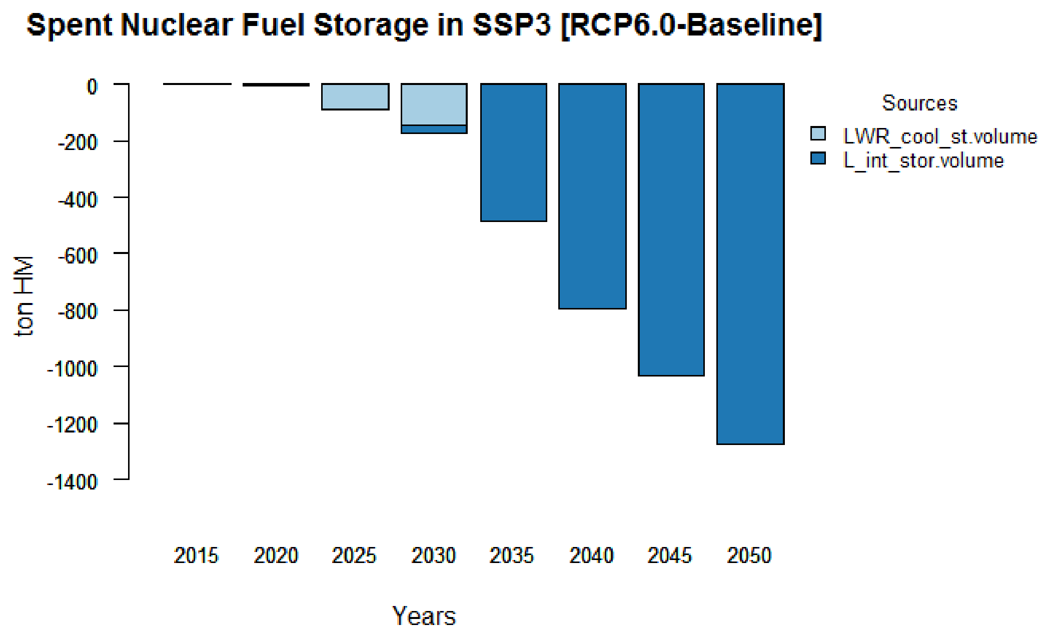

Figure 3.84: Spent nuclear fuel storage difference in SSP3 for RCP6.0

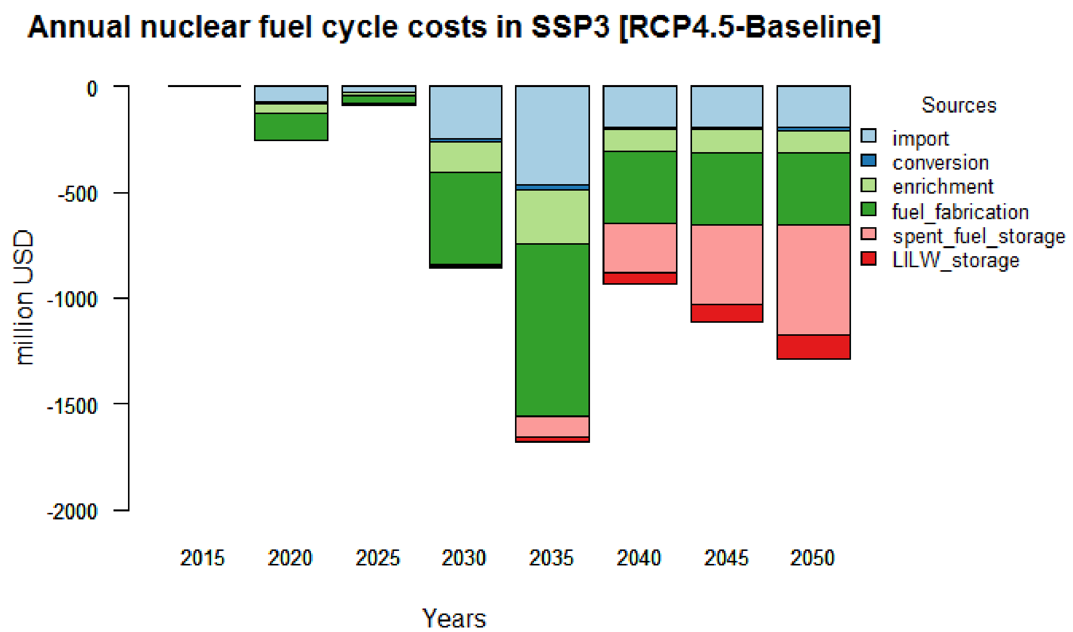

Figure 3.85: Annual nuclear fuel cycle cost difference in SSP3 for RCP4.5

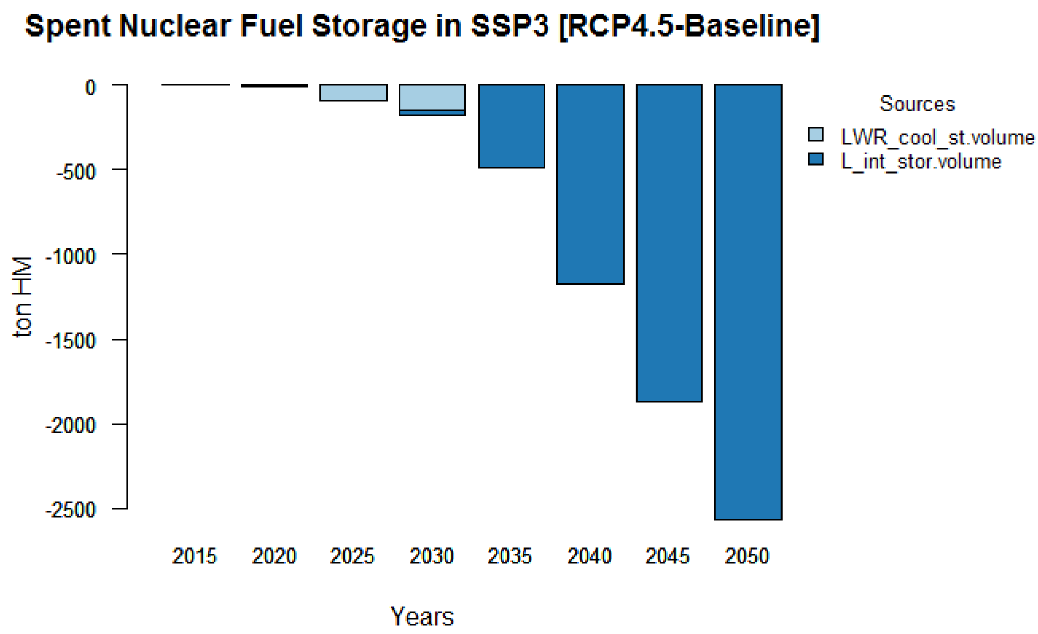

Figure 3.86: Spent nuclear fuel storage difference in SSP3 for RCP4.5

Increasing the climate ambition to RCP3.4 in SSP3 provides similar results for nuclear fuel cycle with RCP4.5 as 4 GW NPP is installed in 2020 remaining constant until the end of the modeling horizon (Figure 3.87). Increasing revenues from CO_2 emissions penalty costs used for subsidizing wind and solar power plants substitutes coal and gas power plants having no affect on the role of nuclear power for achieving this climate target (Figure 3.19).

The result for amount of spent fuel stored for cooling and disposal are similar for RCP3.4 in SSP3 with RCP4.5 stabilizing at 4 GW NPP installed power after 2020 (Figure 3.88). The total amount of spent fuel storage for cooling and disposal reaches 1951 tHM by the end of the modeling horizon which is considerably reduced from 4540 tHM in Baseline scenario.

Nuclear fuel cycle for initial core loading of 4 GW NPP requires 1 billion US$ cost whereas the reduction of cost to 250 million US$ for fresh fuel loading. Investment for nuclear power in MESSAGE uses mixed integer programming with the conditions for cost optimization requiring the feasibility of investing for 1 GW NPP considering

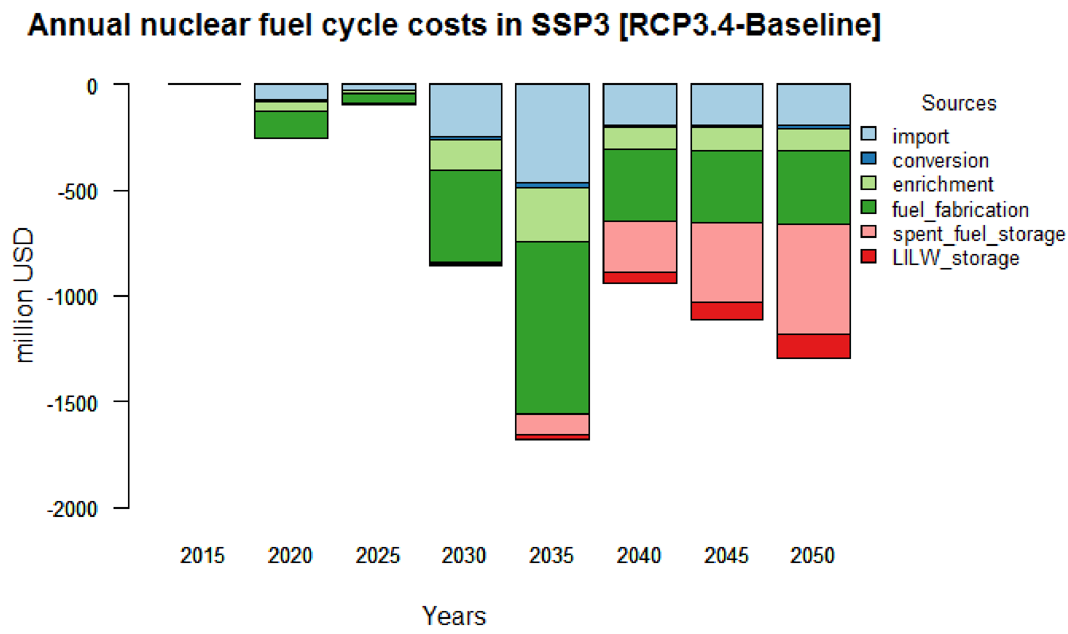

Figure 3.87: Annual nuclear fuel cycle cost difference in SSP3 for RCP3.4

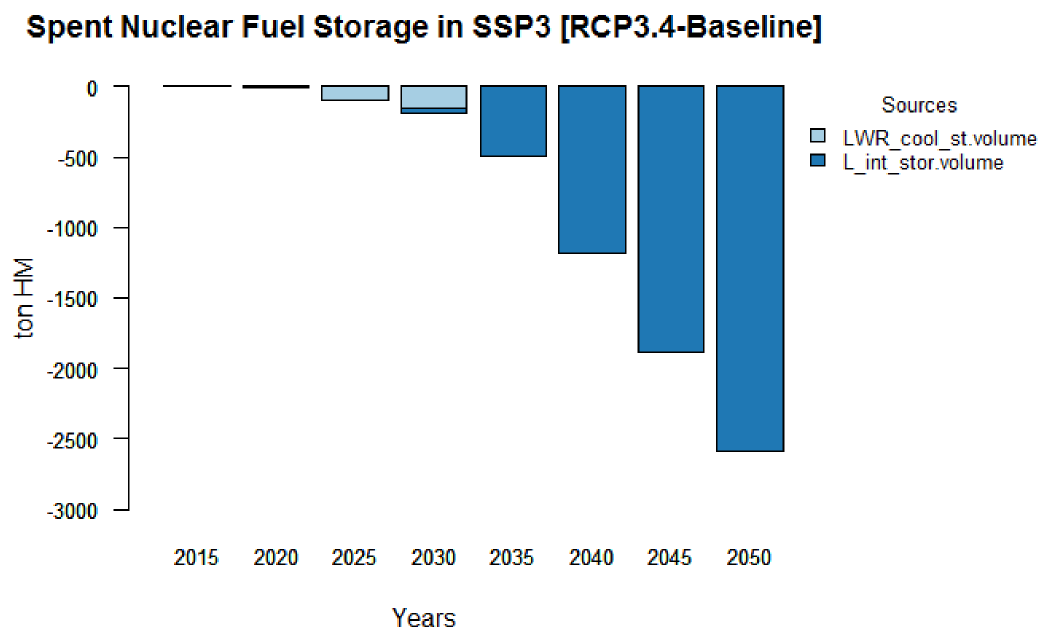

Figure 3.88: Spent nuclear fuel storage difference in SSP3 for RCP3.4

both electricity demand, demand load regions and flexibility of grid to supply fluctuating energy demand. The role of nuclear power for climate mitigation shifts to supporting wind and solar power generation in SSP1 scenario.

The middle-of-the-road narrative of SSP2 reduces the role of nuclear power as increasing revenues from CO_2 emission penalties favors wind and solar power for low carbon transition of the energy system. SSP3 is characterized with higher energy demand due to high population growth and low energy efficiency improvement protecting the role of nuclear power for supplying base load electricity demand.

3.2 Expert elicitation on energy and climate policies

Nuclear energy has the potential to support securing the energy supply systems and decarbonizing the electricity sectors of developing countries. There are already countries stating nuclear energy as one of their climate mitigation strategies in their NDC submissions to the UNFCCC. However investments for innovation in nuclear energy comes from developed countries considering replacement of their aging fleet whereas demand for new nuclear projects comes mainly from developing countries. NPPs are characterized as capital intensive investments and compared with other major infrastructure projects which point out the requirement for reconciling policy intentions with stakeholders concerns for public acceptance and plant modularization to facilitate the construction management [22].

Despite the existing interregional socioeconomic differences, the world has also shifted from a period of national investments for nuclear energy in the 1970s to the current diversification of the energy markets and increasing investment opportunities through international cooperation. Nuclear projects require the involvement of national and international stakeholders ranging from policy makers to utility owners, vendors, regulators, legal and financial institutes, research organizations and the local people living close to the proposed sites.

Experts are selected from members of Energy and Natural Resources Association in Ankara Turkey for conducting a structured survey evaluating the importance given by participants on topics related to global climate change and sustainable development policies with their reflections on national context for future energy system development. The results are analyzed using multiple correlation tests relating the importance given to climate change and energy policies with values and environmental behavior orientations of experts for understanding the intentions of policy makers to consider nuclear energy as an option for mitigation of climate change.

3.2.1 Literature review

There are various studies in the literature relating the personal values [Table 3.12] with environmental behavior by categorizing values based on egoistic, alturistic, hedonic and biospheric orientations [146]. Values are assessed as latent (independent) variables which are measured by using dependent variables on measurable indicators for environmental concern and perception of personal distance to the impact of a potential environmental hazard [148]. Studies assessing the relation between personal values and evaluations related to strategies which deal with environmental concerns presents evidence that value orientations has influence on controversial issues such as climate change and nuclear energy [141].

Table 3.12: Egoistic, altruistic and biospheric values

Values	Dependent variable	Independent variable
Egoistic	Social power	Investment for public education and health
	Wealth	Strengthening of cultural identity
	Authority	Empowerment of national and international institutions
	Influential	Investment for technological development and innovation
Altruistic	Equality	Reduction of inequalities between and within countries
	Peace	Prevention of international and regional conflicts
	Social justice	Strengthening environmental rule-of-law
	Helpful	Empowerment of social charities and relief agencies
Biospheric	Unity	Investment for nature based services
	Protection	Reduction of material and resource consumption
	Respect	Respect for the natural environment and other species
	Nature services	Empowerment of businesses and citizens for nature management

Distance perception to environmental hazard is also related with awareness which can be assessed using game theory method for climate change mitigation as a global commons problem [189]. The study integrates environmental values to economic theory by assessing the relationship between consumption preferences and GDP of countries in order to assess whether this correlation resembles similarities with EKC hypothesis. One of the main drawbacks of the study is the usage of LCOE for renewable energy technologies whereas investment decisions are favorable depending on the marginal prices for maximizing the utility of agents.

However studies based on self-reporting of participants to surveys have limitations related to the participants providing answers perceived as socially correct [143] or being not capable to understand and answer the questions reflecting their true personal behavior [103]. In order to prevent these biases, there are studies performing household surveys using contingency valuation model to assess the benefits and costs of nuclear energy as a climate change mitigation strategy [108]. These studies also present climate mitigation measures related to environmental behavior to reduce energy intensity of production and carbon intensity of energy consumption [179] as alternative options. Psychometric methods contributes to assess the impact of socio-economic characteristics and personal motivation for environmental behavior affects consumption methods to clarify the relation human forcing on the climate [169].

Perlaviciute and Steg [140] review current literature on evaluations and acceptability of energy alternatives based on their characteristics influenced by psychological factors proposing a framework based on perceived benefits and costs. Environmental behavior depends on values which affects their perceptions of climate change[148]. Sustainable energy development decisions are affected by value perceptions of policy makers and relevant stakeholders. Research shows that people with egoistic values tend to support energy options based on the economic benefits whereas biospheric values tend to favor renewable energy options[141].

Nuclear energy as an option for climate change mitigation is assessed in many countries operating an existing fleet and considering new build projects[143]. However nuclear energy also includes concerns for nuclear safety, waste management and proliferation of nuclear weapons[63]. The questions related to nuclear energy are based on the relation with climate mitigation, energy security and related concerns. Additionally mathematical models are sensitive to costs of energy technologies such as the possibility of very cheap or very costly nuclear options which require further elaboration by expert elicitation [19].

3.2.2 Survey method

The study includes the conductance of a structured survey in order to assess the importance of nuclear energy as a potential strategy for climate change mitigation and energy supply security by the participants involved from Energy and Natural Resources Experts Association situated in Ankara Turkey. As currently employed experts have age profiles below 35, additional participants were included from Energy Working Group established by METU Graduates Association.

The value orientations in Table 3.12 are independent (latent) variables in the model given in Figure 3.89 having relations with the personal importance attributions to issues related with SSPs developed for climate change scenarios of the IPCC [151]. The statistics and methods used for the survey are available in Mendeley database under Creative Commons Attribution 4.0 International license [62].

The narratives of SSPs are consulted using expert elicitation [98] survey focusing on the levels of importance using Likert scale (1: Not relevant/applicable, 2: Not important, 3: Slightly important, 4: Moderately important, 5: Important, 6: Very important) given to empowerment of individual (egoistic), social (altruistic) and biospheric values. Survey sample population (n=23) includes energy experts associated with Energy and Natural Resources Association of Turkey and members of METU Graduates Association in order to satisfy diversity in participants ages. Spearman test is used as being less sensitive to outliers for testing the correlation between the importance given to egoistic, altruistic and biospheric values with perception of climate change and nuclear power [160].

The structure of the survey used in the study is based on the assessment of nuclear energy for climate change mitigation strategies and energy policy decisions based on the values given to global and national development strategies and environmental behavior [187]. Energy policy decisions affect both short-term and also long-term interests of nations and the public whereas climate change is perceived as a global problem with unclear endowment rights and time-scale exceeding short-term interests of the public.

The main objective of the study is to assess the impact of personal orientations based on egoistic, altruistic and biospheric values on perceptions for climate change and nuclear power among energy decision makers [39]. Values depend on perception of climate change and nuclear power having relations with the scientific basis of these global issues and environmental behavior of individuals (Figure 3.89).

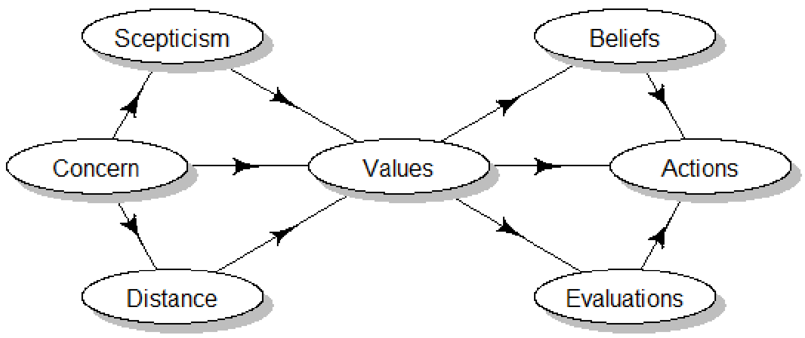

Figure 3.89: Relations used in expert elicitation survey

The importance of "Strengthening of cultural identity" with dependent variable "wealth" is perceived as "moderately important" with wide distribution of answers between "not at all important" and "very important" (Figure 3.90). "Investment for technological development and innovation" with dependent variable "influential" is perceived as "very important" which can be argued as the importance given to technological innovations by energy experts. "Empowerment of national and international institutions" with dependent variable "authority" is perceived as "moderately important" with outliers ranging from "not at all important" to "very important" presenting wide range of opinions. Finally "Investment for public education and health" with dependent variable "social power" is perceived as "very important" presenting the importance given to education for sustainable development. The correlation test between these dependent variables using Spearman method presents that there is positive correlation between "influential" and "social power" variables (α=0.53, p=0.05) whereas there is no significant relation found between remaining variables (Table 3.13).

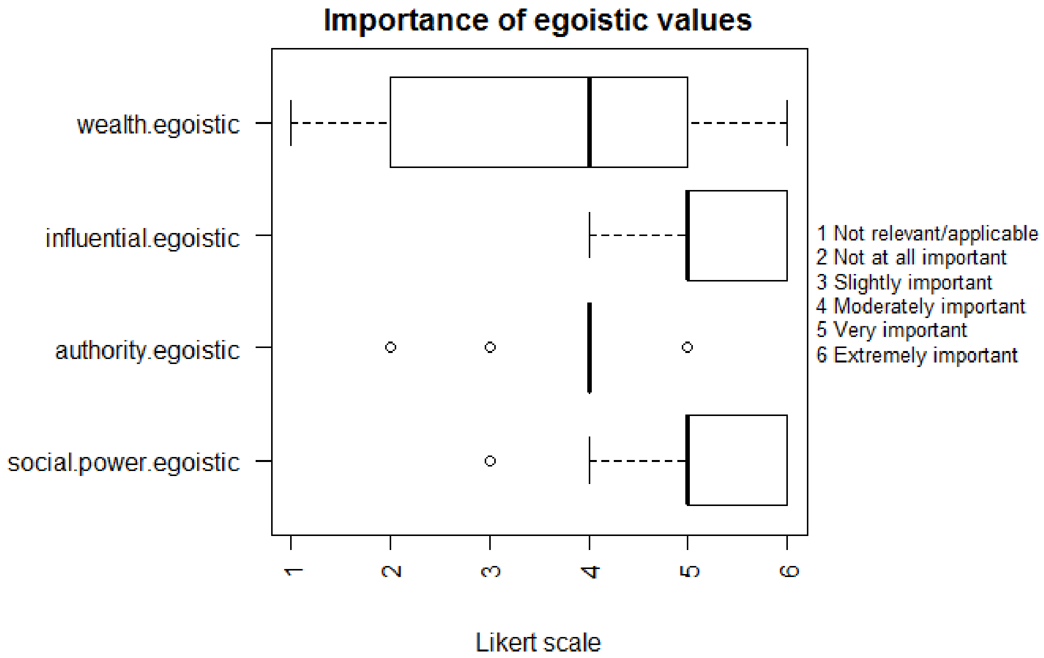

Figure 3.90: Importance of egoistic values

Table 3.13: Relations between dependent variables for egoistic values

	lower.emp	lower.norm	estimate	upper.norm	upper.emp	p
wealth-influential	-0.59	-0.58	-0.15	0.37	0.33	0.60
wealth-authority	-0.40	-0.47	-0.06	0.39	0.43	0.84
wealth-social power	-0.34	-0.31	0.18	0.60	0.59	0.48
influential-authority	-0.40	-0.44	0.02	0.45	0.43	0.98
influential-social power	0.06	0.07	0.53	0.82	0.80	0.05
authority-social power	-0.28	-0.31	0.04	0.39	0.36	0.81

The importance of "Empowerment of social charities and relief agencies" with dependent variable "helpful" is perceived as "slightly important" with first quantile at "not at all important" and third quantile at "moderately important" (Figure 3.91).

"Strengthening environmental rule-of-law" with dependent variable "social justice" is perceived as "extremely important" with first quantile at "very important". Interestingly "Prevention of international and regional conflicts" with dependent variable "peace" is perceived as "moderately important" which has relation with environmental rule-of-law. Finally "Reduction of inequalities between and within countries" with dependent variable "equality" is perceived as "very important" ranging to first quantile with "moderately important". The correlation test between these dependent variables using Spearman method presents that there is negative correlation between "equality" and "social justice" variables (α=-0.41, p=0.05) whereas there is no significant relation found between remaining variables (Table 3.14).

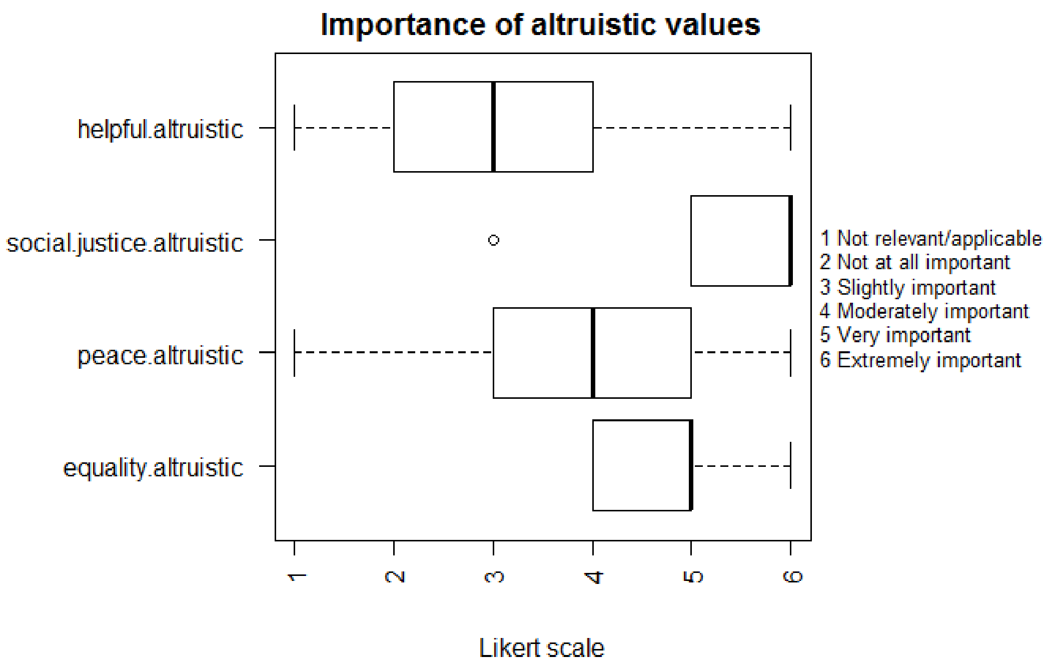

Figure 3.91: Importance of altruistic values

The answers to importance of "Empowerment of businesses and citizens for nature management" with dependent variable "nature services" and "Reduction of material and resource consumption" with dependent variable "protection" present similar distributions with median at "very important" and answers ranging from "moderately important" at first quantile to "extremely important" at third quantile (Figure 3.92). "Investment for nature based services" with dependent variable "unity" is per-

Table 3.14: Relations between dependent variables for altruistic values

	lower.emp	lower.norm	estimate	upper.norm	upper.emp	p
helpful-social justice	-0.64	-0.63	-0.12	0.41	0.36	0.62
helpful-peace	-0.17	-0.20	0.37	0.80	0.78	0.21
helpful-equality	-0.37	-0.39	0.07	0.56	0.53	0.68
social justice-peace	-0.75	-0.74	-0.34	0.21	0.22	0.23
social justice-equality	-0.67	-0.69	-0.41	-0.03	-0.03	0.05
peace-equality	-0.22	-0.22	0.24	0.67	0.65	0.28

ceived as “very important” ranging to “extremely important” at third quantile. Finally “Respect for the natural environment and other species” with dependent variable “respect” is perceived as “extremely important” ranging to “very important” at first quantile. The correlation test between these dependent variables using Spearman method presents that there is positive correlation between “nature services” and “unity” variables (α=0.48, p=0.04) whereas there is no significant relation found between remaining variables (Table 3.15).

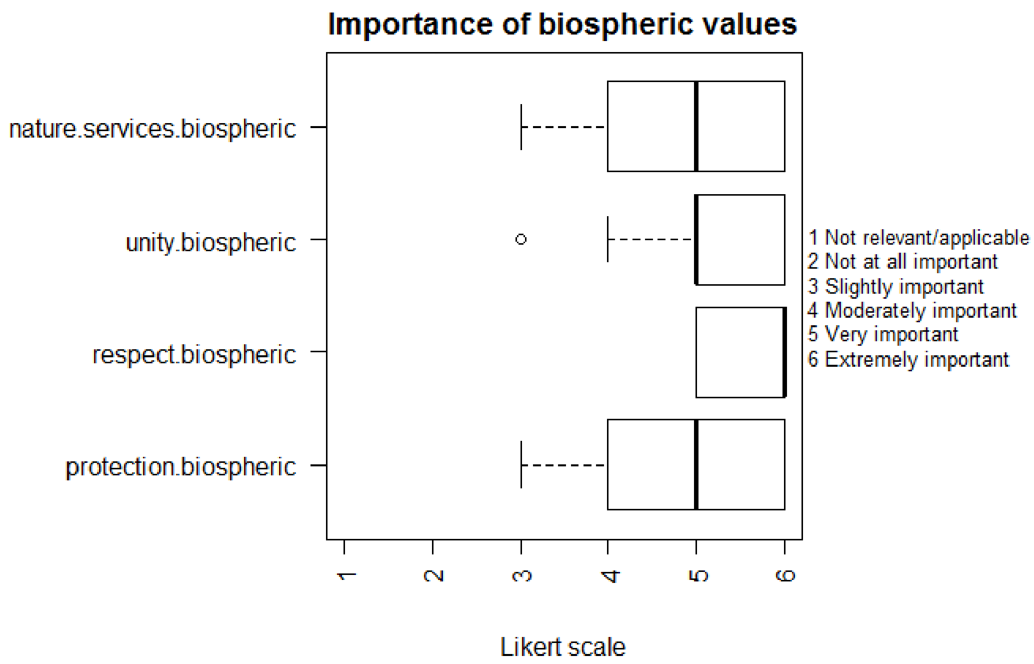

Figure 3.92: Importance of biospheric values

Table 3.15: Relations between dependent variables for biospheric values

	lower.emp	lower.norm	estimate	upper.norm	upper.emp	p
nature services-unity	0.18	0.09	0.48	0.80	0.80	0.04
nature services-respect	-0.54	-0.59	-0.19	0.32	0.34	0.51
nature services-protection	-0.20	-0.25	0.27	0.66	0.66	0.33
unity-respect	-0.38	-0.40	0.05	0.48	0.49	0.83
unity-protection	-0.17	-0.10	0.30	0.61	0.56	0.16
respect-protection	-0.45	-0.45	-0.02	0.37	0.33	0.83

These dependent variables can be related to clusters representing value orientations of sample group using Very Simple Structure factor model of complexity one (Figure 3.93) [150]. The reliability of this cluster model is determined by the mean split half correlation parameter α and the worst split half correlation parameter β for all clusters. The general result of this model shows that there is negative relation between dependent parameters for altruistic and biospheric value orientations and a weak correlation of them with dependent variables related with egoistic value orientations.

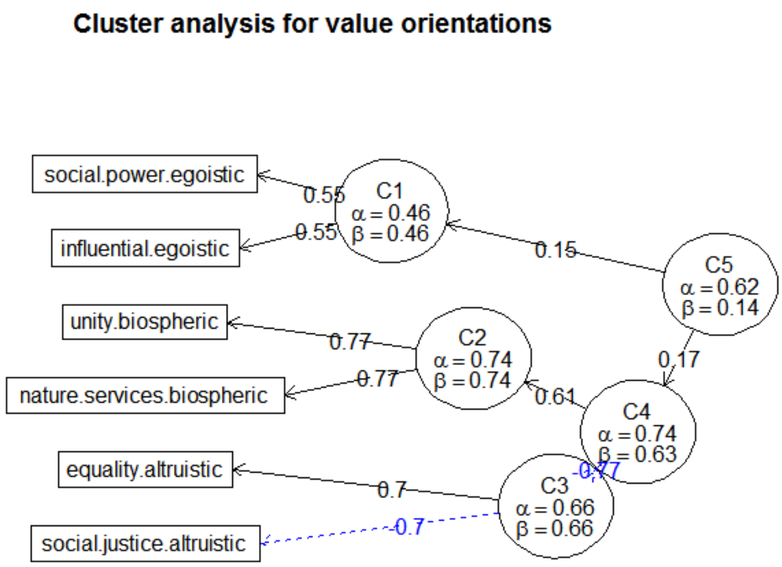

Figure 3.93: Cluster model for value orientations

3.2.3 Climate change and nuclear power

Demographic variables used in the model as control parameters are gender, age, professional background and highest degree earned in school by survey participants. The population of survey includes members of Energy and Natural Resources association (N=53) 28% represented by female participants. The sample population includes 16 participants from this group with a higher representation of females to reduce gender bias in responses (Figure 3.94).

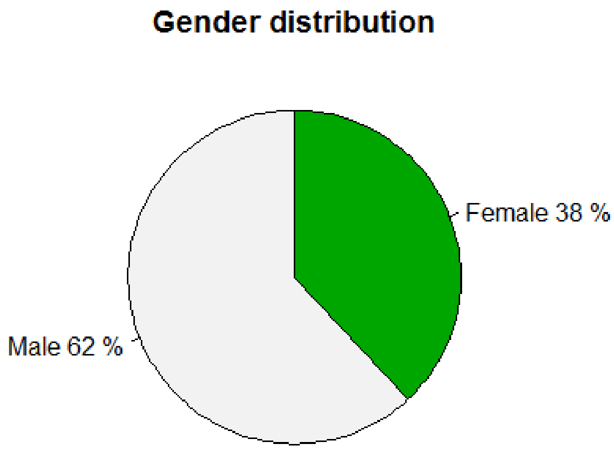

Figure 3.94: Gender distribution of sample population

The first energy experts in Ministry of Energy and Natural Resources were employed in 2012 which limits the variation of ages in sample population. In order to reduce the potential bias from focusing on young experts, the sample population was extended with additional three experts from Energy Commission of METU Graduates Association also increasing the sample population (n=21) (Figure 3.95).

The professional distribution of sample population is equally weighed with 48% represented by engineers and the remaining 52% are represented by social and statistical scientists, law and other professions (Figure 3.96). The age profile of sample pop-

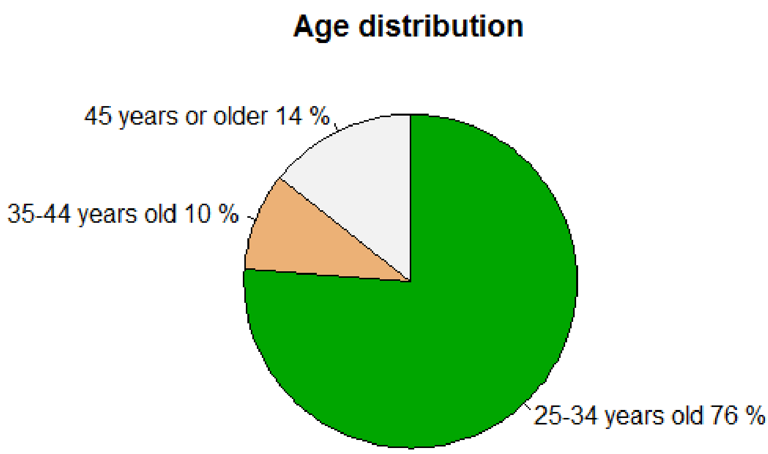

Figure 3.95: Age distribution of sample population

ulation corresponds to educational degrees possessed by them 62% of participants possessing a Bachelors degree (Figure 3.97).

Analysis of variance (ANOVA) method is used for assessing the perceptions of climate change and nuclear power based on the control variables [31]. The control variables are grouped in two as gender-age and profession-degree in order to elaborate the potential affect of combination of variables on the answers of sample group.

The survey question “"Thinking about the causes of climate change, which, if any, of the following describes your opinion?"” with dependent variable “climate change” is answered by 16 participants from sample population (n=21) as “Climate change is happening now, and is entirely related to human activities”. Using two-group ANOVA method with gender and age as control variables shows that although the median of answers for both groups is “Very important”, there is significant difference between male and female participants (F=3.546, p=0.07). However there is no significant difference for age (F= 2.532, p=0.13) and combination of gender and age (F=1.226, p=0.284) of participants for climate perception (Figure 3.98).

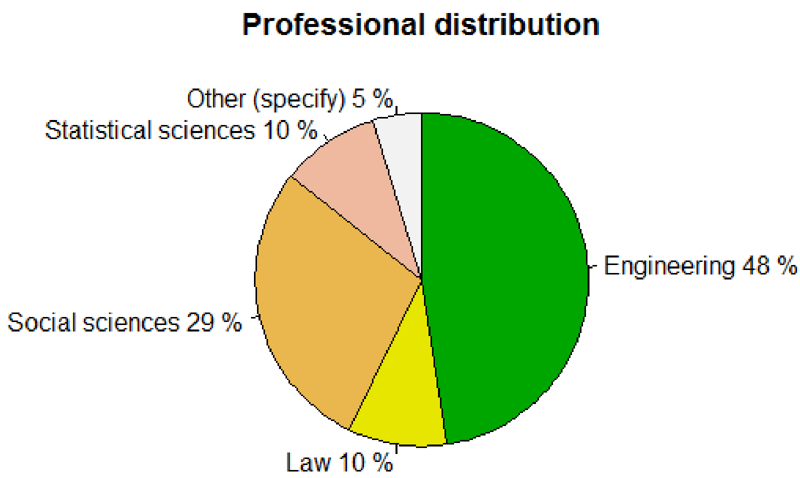

Figure 3.96: Profession distribution of sample population

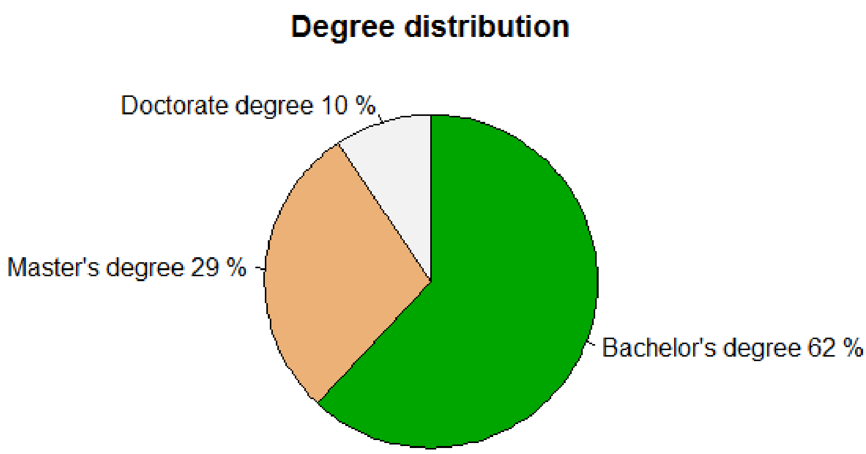

Figure 3.97: Degree distribution of sample population

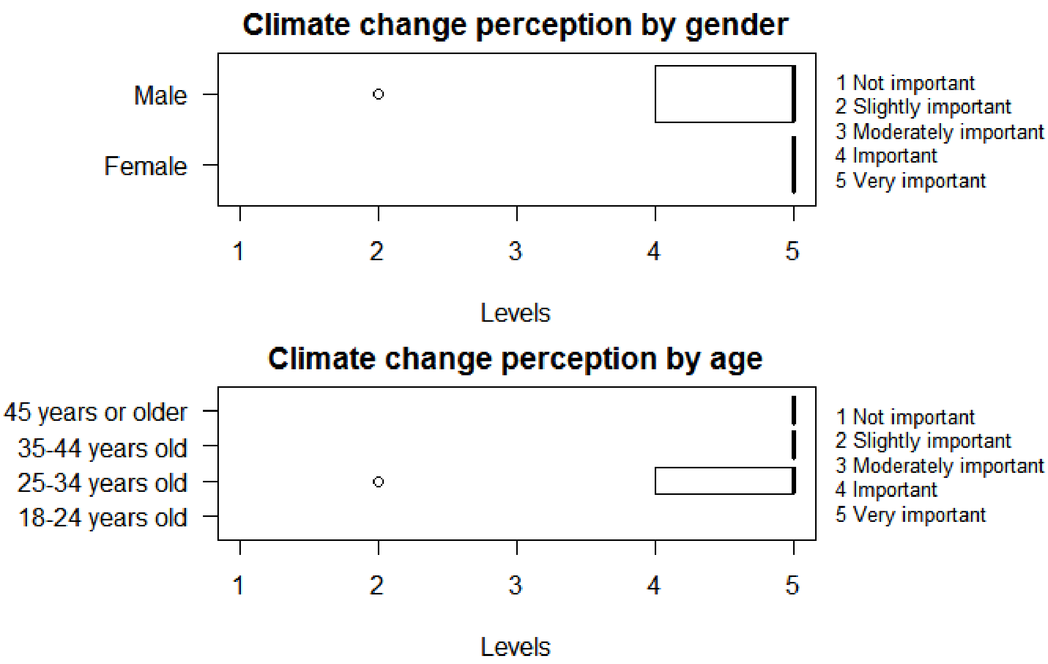

Figure 3.98: Climate change perception for gender and age

Analyzing the dependent variable "climate change" for profession and degree as control variables presents that there is no significant difference in the answers for professions (F=0.487, p=0.495), degrees (F=0.138, p=0.714) and combination of professions and degrees (F=0.002, p=0.968) of participants (Figure 3.99). The answers to this question are subject to bias as it was the first question of the survey with "climate change" being the subject favoring the acceptance of this issue.

The survey question "Which of these two issues, if at all, do you think is more important? Climate change - reducing the carbon emissions from human activities to prevent irreversible damage to the environment. Energy security - ensuring the supply and access of uninterrupted, secure and affordable energy for all." with dependent variable "climate-energy tradeoff" is answered by 12 participants from sample population as "Both are equally important". Two-group ANOVA method shows that there is significant difference for both gender (F=3.293, p=0.0873) and age (F=7.958, p=0.0118) of participants (Figure 3.100). Interestingly the median of answers are "Both are equally important" for both genders whereas the median answer of participants with ages 35 and above shifts to "Both - but climate change has higher

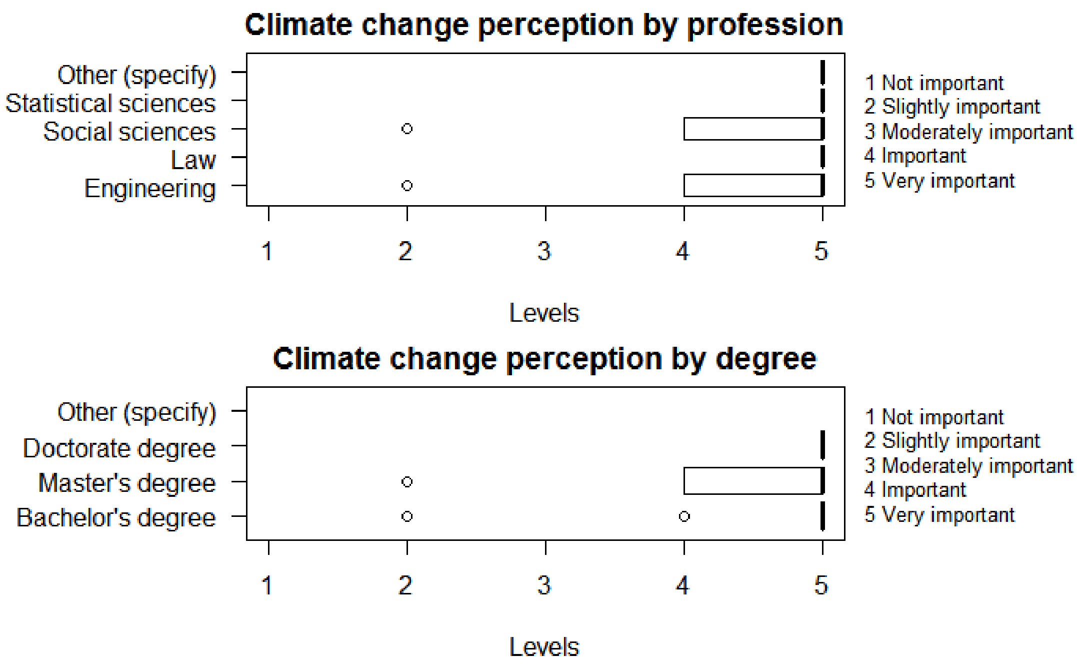

Figure 3.99: Climate change perception for profession and degree

priority"'.

Analyzing the dependent variable "climate-energy tradeoff" for profession and degree as control variables shows that there is significant difference for professions (F=4.605, p=0.0466) with median of answers of engineers as "Both - but climate change has higher priority". Analysing the combined affect of profession and degree shows that there is no significant difference (F=0.243, p=0.6285) in the answers of participants (Figure 3.101).

The survey question "Thinking about nuclear energy as an option for climate change mitigation, which, if any, of the following describes your opinion?" with dependent variable "nuclear energy" is answered with a wide range from "We should explore all other energy options to reduce our carbon emissions before building a new nuclear power plant" in the first quantile to "We need nuclear energy because we are not able to reduce our carbon emissions by using all other energy options" in the third quantile. Two-group ANOVA method shows that there is no significant difference for both gender (F=0.004, p=0.951) (Figure 3.102) and age (F=1.669, p=0.214) (Figure

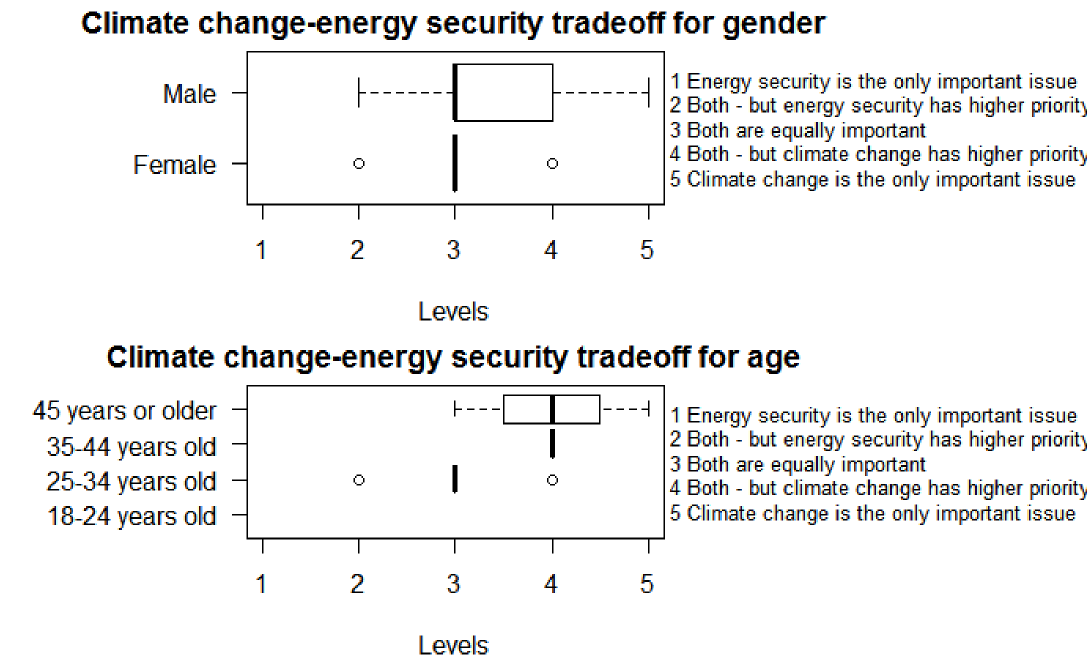

Figure 3.100: Climate change-energy trade-off and gender

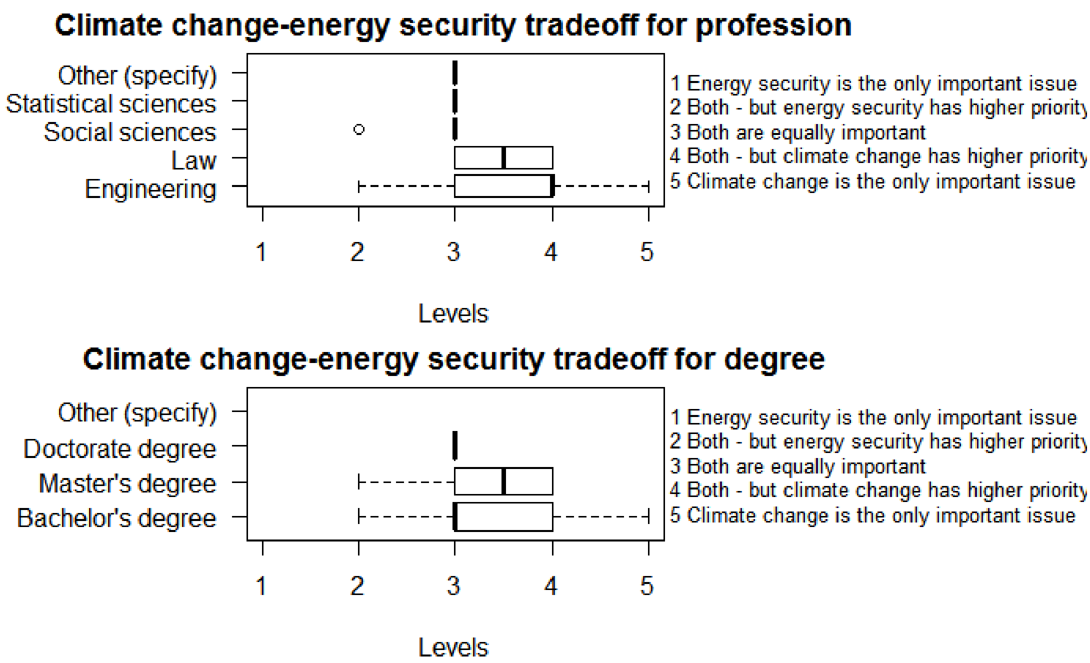

Figure 3.101: Climate change-energy trade-off and profession

3.103) of participants.

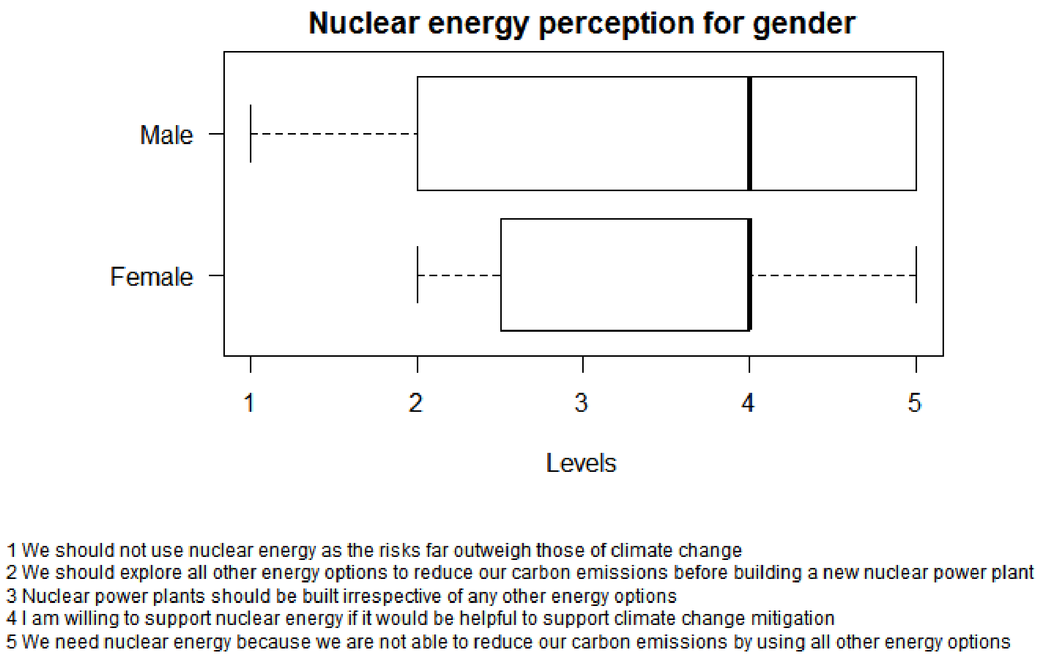

Figure 3.102: Nuclear energy perception for gender

Analyzing the dependent variable "nuclear energy" for profession and degree as control variables shows that there is no significant difference for professions (F=0.183, p=0.675) (Figure 3.104) and degrees (F=0.432, p=0.520) (Figure 3.105) of participants. We can analyze that responses for the perception of participants for nuclear energy are evenly distributed for all control groups.

3.2.4 Results and discussion

The global questions used in the survey assess the perception of participants towards climate change, climate-energy nexus and nuclear energy. Likert scale from "1" to "5" is used for answers reflecting the degree of perceptions to these issues. Factual questions concerning perception of climate change and nuclear energy have answers starting from "There is no such thing as climate change" or "We should not use nuclear energy as risks outweigh those of climate change" for scale of "1" to "Climate change is happening now and is entirely related to human activities" and "We need

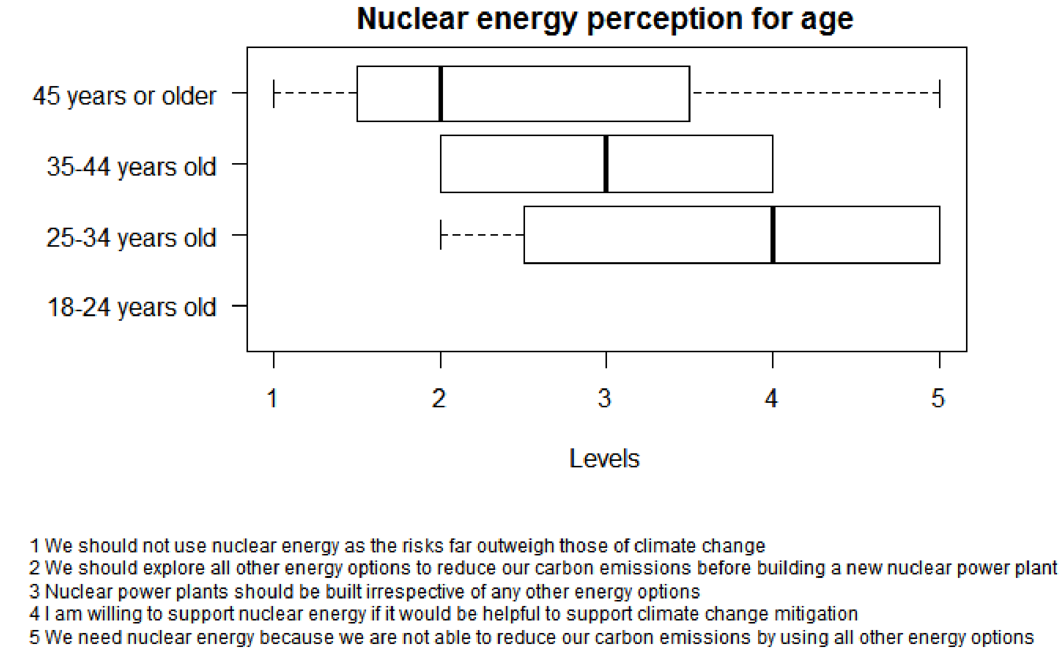

Figure 3.103: Nuclear energy perception for age

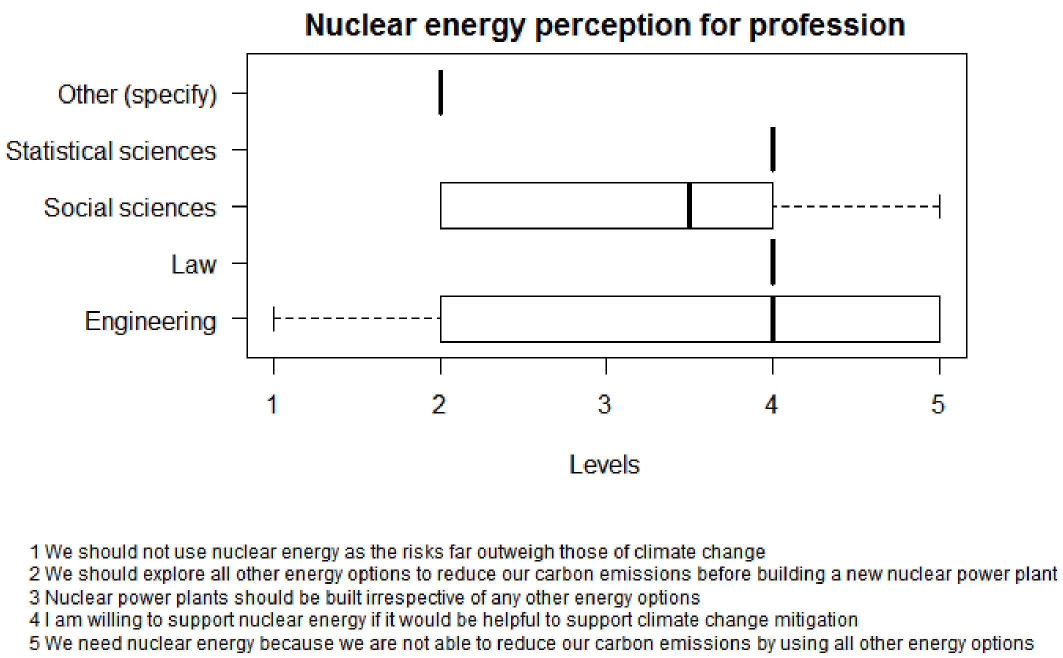

Figure 3.104: Nuclear energy perception for profession

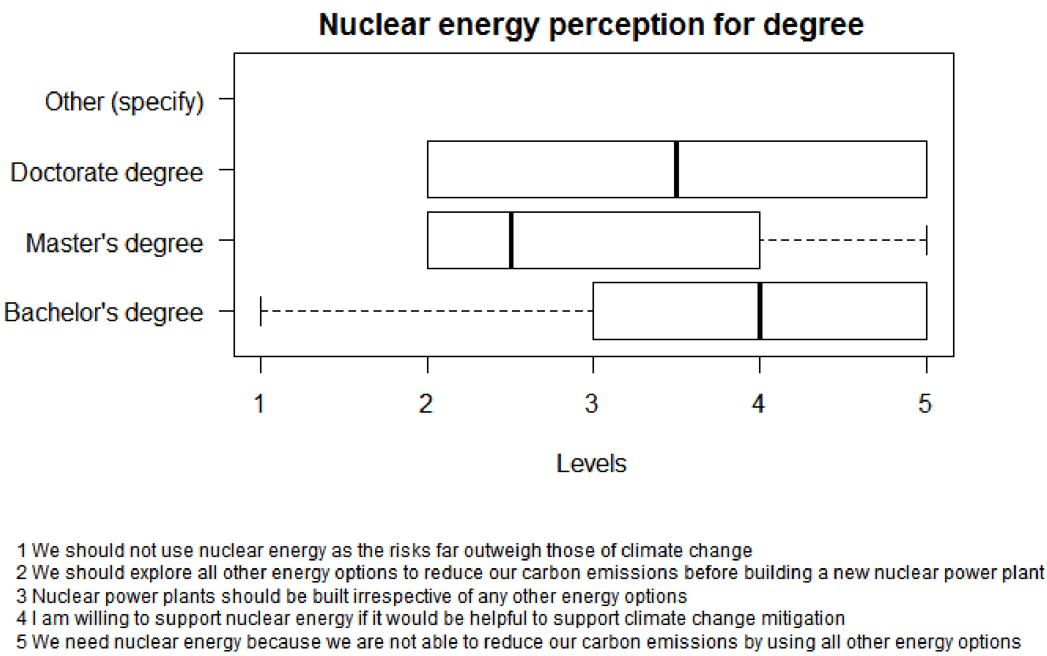

Figure 3.105: Nuclear energy perception for degree

nuclear energy because we are not able to reduce our carbon emissions by using all other energy options” for scale of “5”. The median results show that “Climate change is happening now, and is entirely related to human activities” (n=21, skew=-1.65), “Both climate change and energy security are equally important” (n=21, skew=0.35) and "I am willing to support nuclear energy if it would be helpful to support climate change mitigation" (n=21, skew=-0.26).

The reliability of answers given to survey questions are checked by using multiple correlation tests. As the title of the survey is directly linked to “climate change” and “role of nuclear energy” this method is useful in order to identify potential biases in the answers. There is no significant positive correlation between the answers given to questions on climate change and climate-energy nexus (α=0.26, p=0.17). These are further checked with answers given to questions related with environmental behavior showing that answers of climate-energy nexus have some correlations with environmental behavior therefore are considered more reliable compared to answers of climate change. There is significant negative correlation between answers given to climate-energy nexus and modes of transport (α=-0.43, p=0.04) which is the basis for selection of this question for further analysis of energy system modeling results.

The perception of nuclear energy is evaluated by the potential role for climate mitigation, importance as an energy resource and safety of nuclear power facilities. There is significant positive correlation between the role of nuclear power for climate mitigation and the importance of nuclear power (α=0.56, p=0.02) asked as "How important, if at all, do you perceive nuclear energy for safe and reliable electricity generation?" with median response of "Important" (n=21, skew=-1.04) from participants. There is no significant relation between the importance given to nuclear energy - both for climate mitigation and as an energy source - and perception of nuclear safety from nuclear power plants (n=20, skew=0.76) and nuclear fuel facilities (n=20, skew=1.01) with median response of "Slightly safe". The question related to safety of radioactive waste management facilities, which is one of the major issues related to sustainability, is answered with median response of "Not at all safe" (n=20, skew=1.44) having positive correlation with perception of safety from nuclear power plants (α=0.77, p=0.02).

The results are useful as a preliminary evaluation of policy makers of Turkey as a developing country for assessment of climate change and the role of nuclear power for climate mitigation and as a sustainable energy resource. However there are limitations on the reliability of answers given to questions which are checked with their correlations related with the value perceptions and environmental behavior of participants. The perception of experts on climate-energy tradeoff has significant relation with their importance given to "Respect for the natural environment and other species" with dependent variable "respect" selected as biospheric value orientation (Table 3.16).

However the perception of nuclear energy has significant negative correlation with the importance given to "Reduction of material and resource consumption" which is attributed as one of the climate change mitigation measures mentioned in the narrative of SSP1 green transformation pathway (Table 3.16) . These results show that energy policy makers in developing countries consider the importance of nuclear energy as a domestic issue whereas climate change requires international norms for global climate action. Although there is also concern for nuclear and radiation safety related to nuclear power generation for now, this could be raised as an issue in future for new-build projects there is lack of experience in these issues.

Table 3.16: Relations between perceptions and environmental values

	lower.emp	lower.norm	estimate	upper.norm	upper.emp	p
climate-energy tradeoff - respect	0.35	0.34	0.59	0.79	0.8	0
nuclear energy - protection	-0.79	-0.75	-0.42	0.05	0	0.1

The answers given to the survey question “How important, if at all, do you perceive the following energy sources for safe and reliable electricity generation?” for renewable energy sources favors solar (n=20, skew=-1.03) and wind power (n=20, skew=-1.03) with median value between “Important” and “Very important” (Figure 3.106). Importance given to nuclear energy (n=20, skew=-1.04) has the same median value “Important” with hydro-power (n=20, skew=-0.58), geothermal (n=20, skew=-0.13) and biomass (n=20, skew=-0.65).

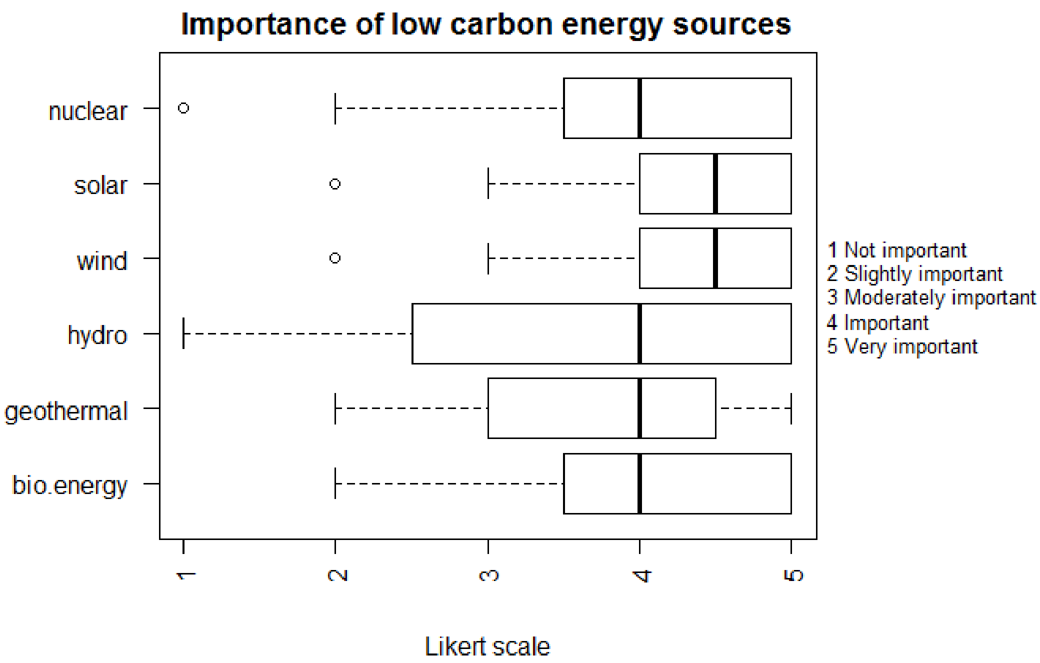

Figure 3.106: Importance of low carbon energy sources

The answers given to the survey question “How important, if at all, do you perceive the following energy sources for safe and reliable electricity generation?” for fossil energy sources favors domestic coal (n=20, skew=-0.15) with median value between “Moderately important” and “Important” (Figure 3.107). Natural gas is ranked as second with median value “Important” (n=20, skew=0.25), followed by import coal with median value “Slightly important” (n=20, skew=1.18) and finally oil with median value “Not important” (n=20, skew=1.36).

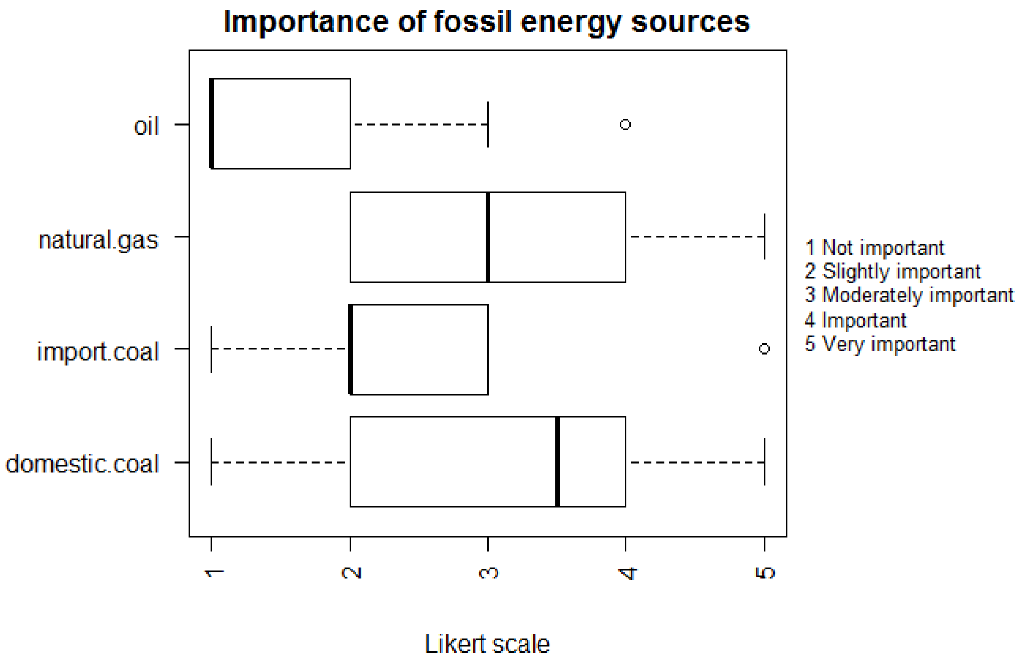

Figure 3.107: Importance of fossil energy sources

The perception of safety for industrial facilities is affected by the NIMBY behavior where local impacts are more important [34]. These results are independent from energy technology costs as people place high value to where they live. The highest perception of safety is given to wind and solar power plants (n=20, skew=-1.21) with median value between “Very safe” and “Extremely safe” and the second place given to hydro-power (n=20, skew=-0.64) with median value “very safe” (Figure 3.108). Electricity generation from biomass (n=20, skew=0.28) has median value “moderately safe” being the lowest for renewable energy sources. The perception of safety from nuclear power (n=20, skew=0.76) is “slightly safe” which is above for coal power plants (n=20, skew=0.98) with median value between “not at all safe” and “slightly safe” and below gas power plants (n=20, skew=0.17) with median value between “slightly safe” and “moderately safe”.

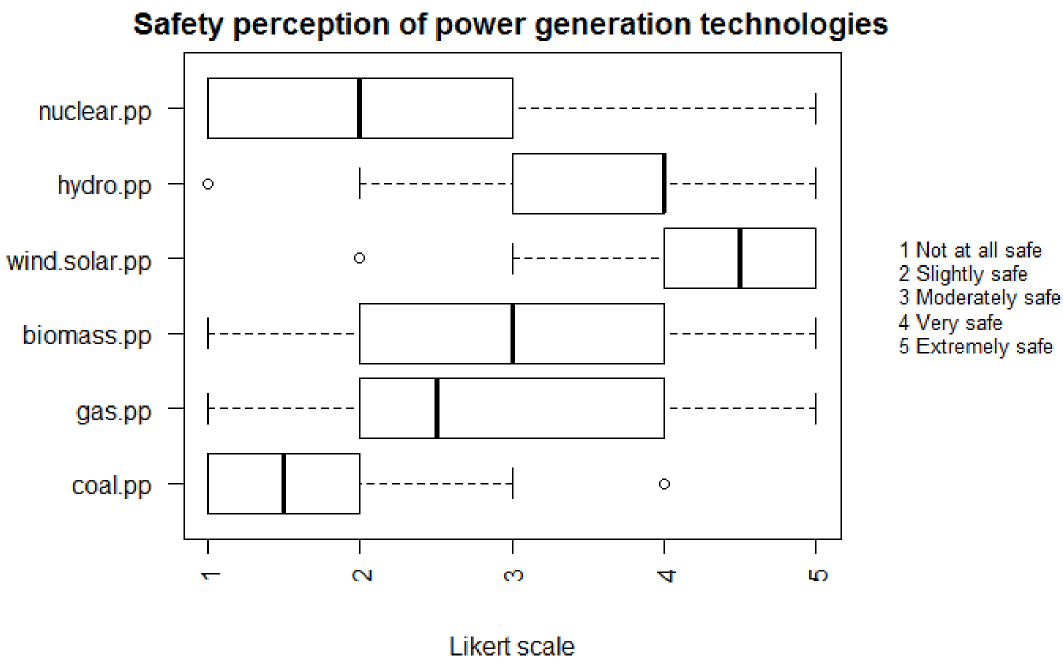

Figure 3.108: Safety perception of power generation technologies

The energy supply system includes infrastructure for transforming primary energy sources for final energy demand. These technologies also have relations with the power sector for both using the same primary energy sources and also as conversion for transforming them to secondary energy sources with potential for reprocessing and re-usage depending on social preferences [28]. Facilities for nuclear fuel production and radioactive waste storage are part of the nuclear fuel cycle with the median value “slightly safe” for nuclear fuel (n=20, skew=1.01) and “not at all safe” for radioactive waste (n=20, skew=1.44) (Figure 3.109). Oil refinery producing oil products for final energy demand and fuel-oil for power sector are perceived as “slightly safe” (n=20, skew=0.92) whereas gas processing and storafe facilities have higher level of safety perceived with median value “moderately safe” (n=20, skew=-0.37). Finally solid waste landfill facilities which can be linked with biomass power generation are perceived as “slightly safe” (n=20, skew=-0.95) [15].

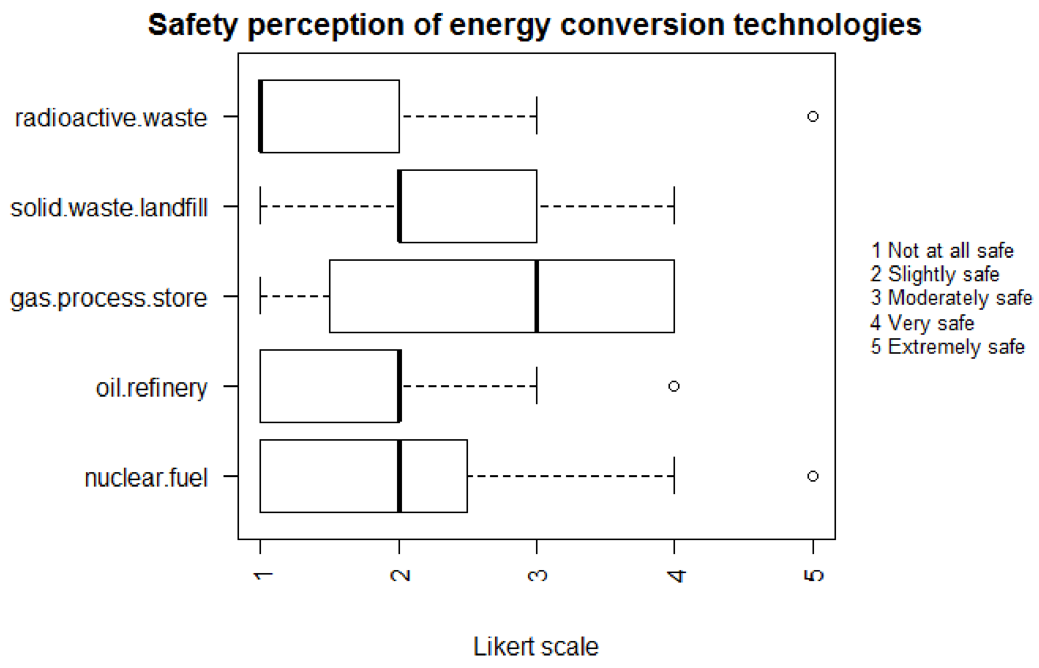

Figure 3.109: Safety perception of energy conversion technologies

3.3 Sensitivity analysis

Analytical modeling results are sensitive to assumptions on activity and constraint variables. Optimization of the energy system costs depends on the prices of energy sources and conversion technologies as well as environmental or other socio-economic constraints. In order to assess the sensitivity of the results to these assumptions both quantitative and qualitative analysis are performed for future scenarios.

Chen et al. [32] analyze whether general equilibrium models generate reliable projections based on energy and environmental policies based on consumer preferences and historic trends. The results present significant challenges for very low GHG emission pathway as an industrialized world without fossil fuels has not been experienced in the past. Models including endogenous technological change are further subject to sensitivity of parameters such as the learning rate and spillover affects [58].

The linear programming solver of MESSAGE generates ranges for pareto-optimal solution including cost coefficients used in the objective function, upper and lower constraint bounds for right hand side equations and variable bounds for activity and capacities of energy conversion technologies calculated by the model for optimization of the total discounted cost of the energy system. However these rates are based on literature therefore are not included to the sensitivity analysis for this study.

Sensitivity analysis for coefficients of variables in the objective function are affected by the costs of energy conversion activities and capacities based on the IAM results of SSPs. The energy system is driven by primary energy supply of fossil fuels and low carbon energy sources being nuclear energy and biomass. The results are also sensitive to right-hand-side constraints for the feasible generation capacity from renewable energy sources. Finally the model results are sensitive to bounds for variables which are technical constraints for power ramp-up and ramp-down rates [27].

The modeling results are not sensitive to extraction costs in the short term due to abundant capacity exceeding final energy demand (Figure 3.110). The sensitivity to maximum prices for domestic coal increases in the long term due to the transformation of energy sector to low carbon future. The sensitivity of import coal prices is high in the short term which decreases after 2035 which coincides with rapid penetration of wind and solar power generation (Figure 3.7). The sensitivity of results to oil import prices is high for increasing costs and to gas for decreasing costs in the short term. This difference is due to the capacity investment available for natural gas pipelines in the beginning of the modeling period whereas final energy demand for oil products are complemented by additional imports.

The sensitivity to increase of uranium import prices for Baseline scenario in SSP1 decreases by the end of the modeling horizon whereas the reduction of prices to zero calculate the same pareto-optimal solution (Figure 3.111). The results is similar for biomass in the beginning of the modeling horizon whereas the range of biomass production costs decreases during the modeling horizon. Biomass is used for both final energy demand, electricity generation from biomass plants and biodiesel production. The subsidy given to biomass power plants by FITs from revenues generated by CO_2 emission penalty costs creates increasing sensitivity to biomass costs.

The climate ambition for RCP2.6 increases the sensitivity of modeling results to coal import costs after 2035 which is considered as one of the favorable electricity gen-

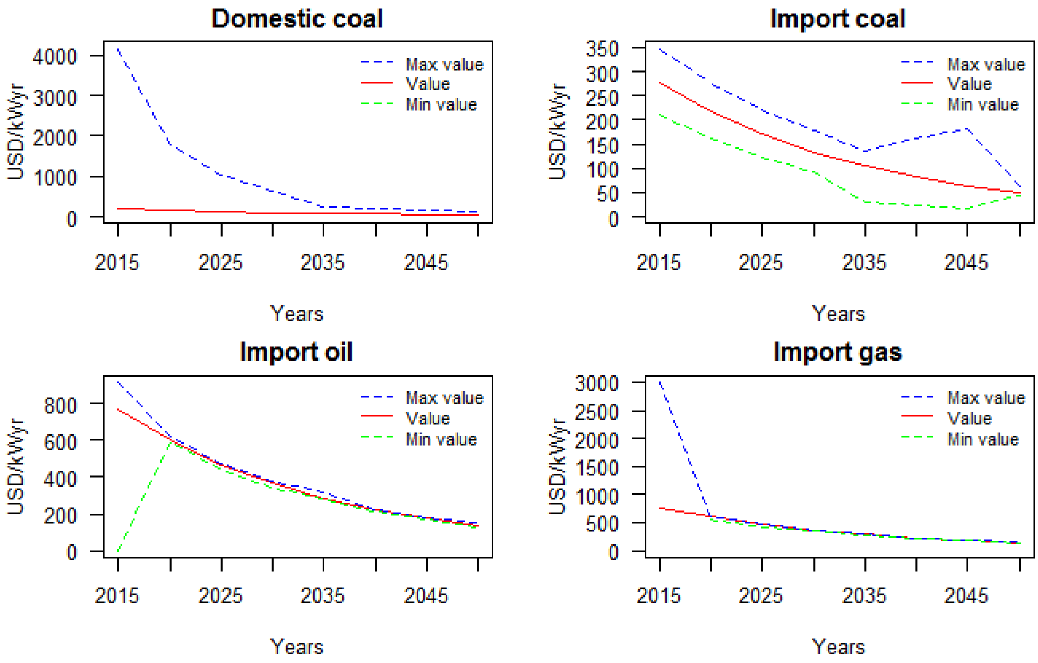

Figure 3.110: Primary fossil fuel costs for Baseline in SSP1

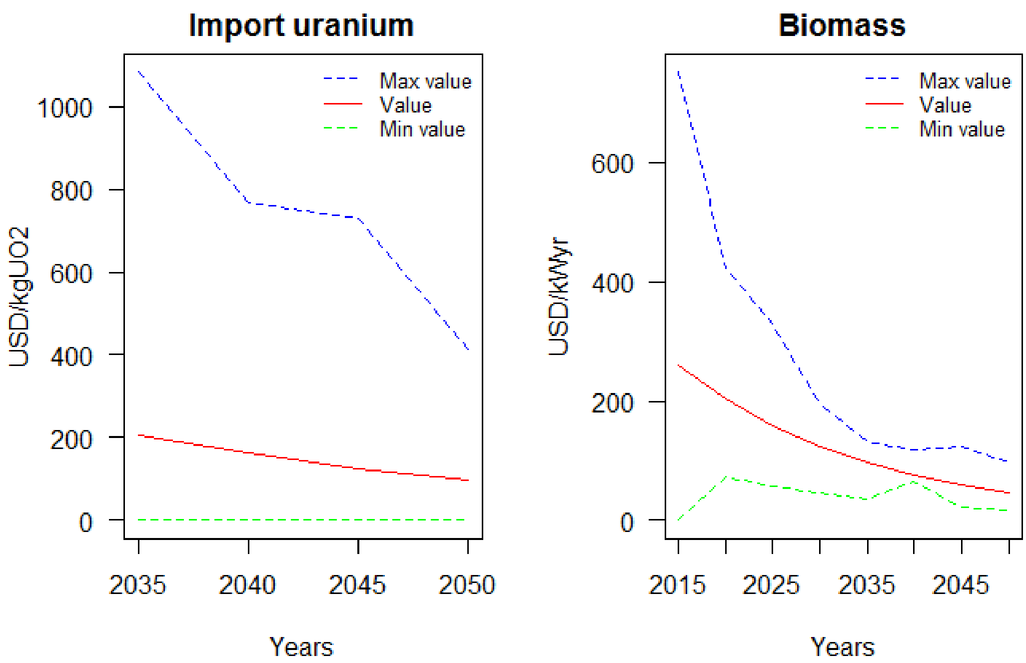

Figure 3.111: Low carbon fuel costs for Baseline in SSP1

eration sources due to low costs and high conversion efficiencies compared to other fossil fuels (Figure 3.112). The sensitivity to costs of domestic coal, import oil and gas are similar to Baseline scenario in SSP1 which are more driven by final energy demand compared to CO_2 emission penalty costs.

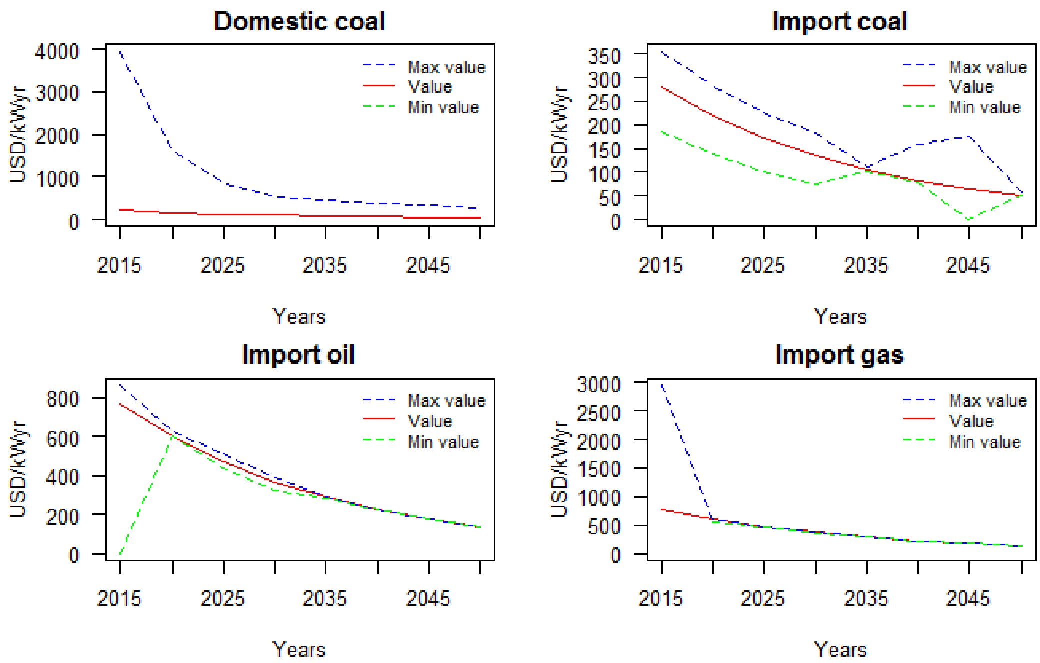

Figure 3.112: Primary fossil fuel costs for RCP2.6 in SSP1

The import prices of uranium affect the modeling results only in 2035 for RCP2.6 scenario in SSP1 which is the period of transition to low carbon energy system with additional massive investment to wind and solar power generation (Figure 3.113). The sensitivity to biomass prices remain higher for RCP2.6 in SSP1 compared to Baseline scenario after 2035 which is determined by increasing CO_2 emission penalty costs.

Final energy demand in SSP2 is characterized with higher rate of increase due to higher population growth and lower improvement in energy efficiency compared to SSP1. Final energy demand for import coal is more sensitive to costs for Baseline scenario in SSP2 compared to SSP1 scenarios (Figure 3.114). The results are not sensitive to domestic coal extraction costs in the short term with increasing sensitivity by the end of the modeling horizon. The costs of oil and gas import affect the modeling results after 2025 as a result of idle capacity in power sector in the begin-

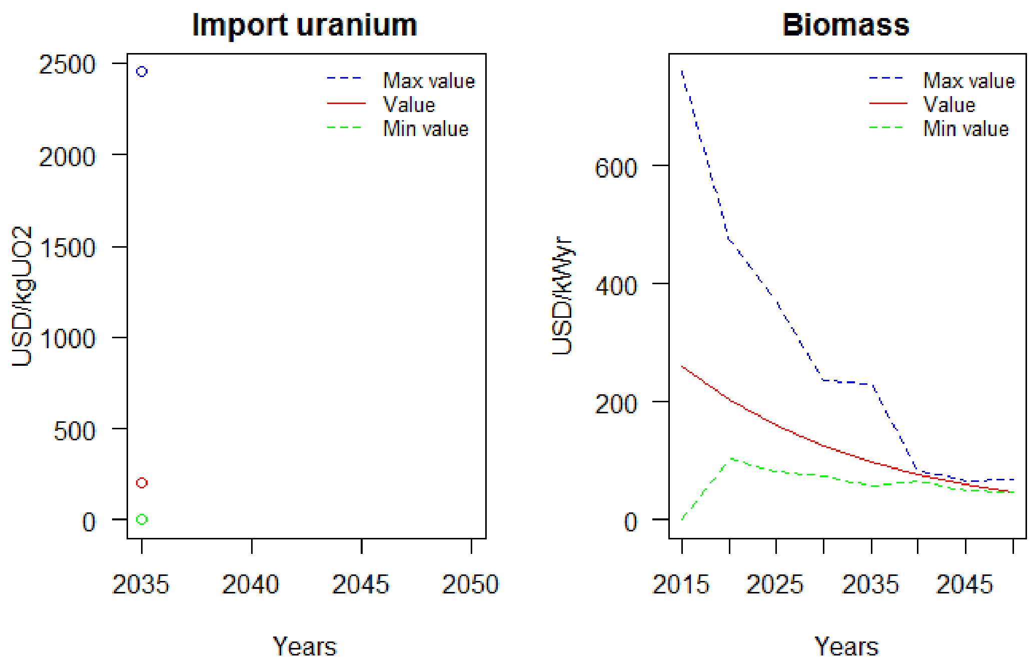

Figure 3.113: Low carbon fuel costs for RCP2.6 in SSP1

ning of the modeling horizon.

The sensitivity of modeling results to uranium import costs increases for Baseline scenario in SSP2 increases with penetration of nuclear electricity generation to power sector after 2035 (Figure 3.115). However the results are sensitive to decreases in uranium import costs during all modeling horizon which would affect the temporal scale of NPP deployment. The sensitivity of results to biomass costs decreases during all modeling horizon whereas maximum costs for import uranium increases in the beginning of the modeling period which can be related to lack of pricing mechanisms to subsidize nuclear energy for early penetration to the power sector.

3.4 Validation of the hypothesis

Electricity generation from nuclear energy is considered as one of the strategies for both energy security and climate mitigation of developing countries whereas developed countries consider the costs and benefits of NPPs in order to make decisions

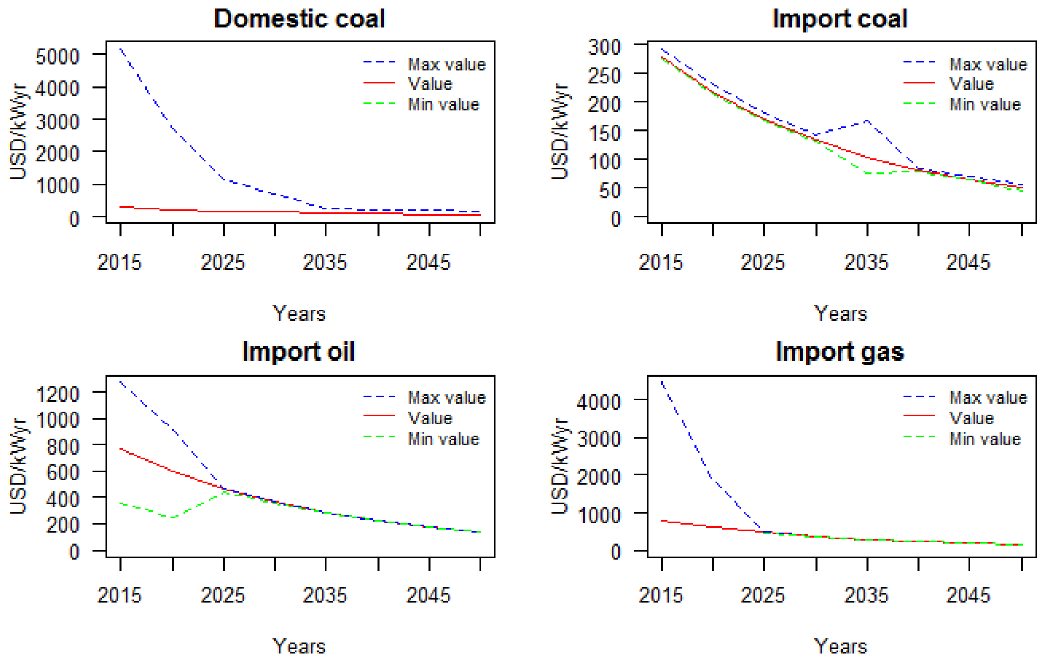

Figure 3.114: Primary fossil fuel costs for Baseline in SSP2

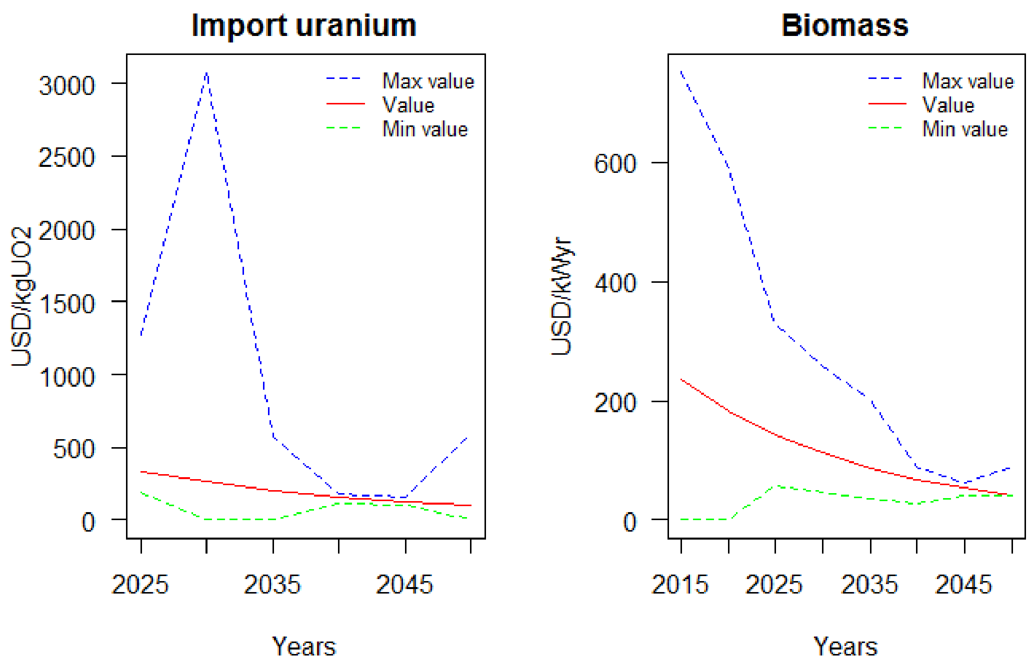

Figure 3.115: Low carbon fuel costs for Baseline in SSP2

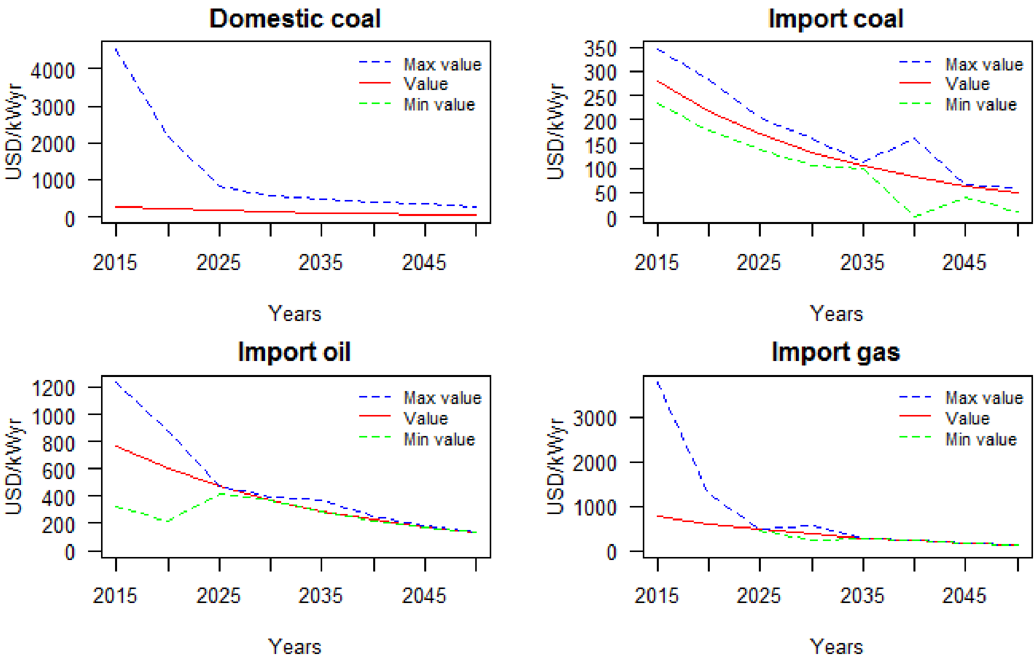

Figure 3.116: Primary fossil fuel costs for RCP2.6 in SSP2

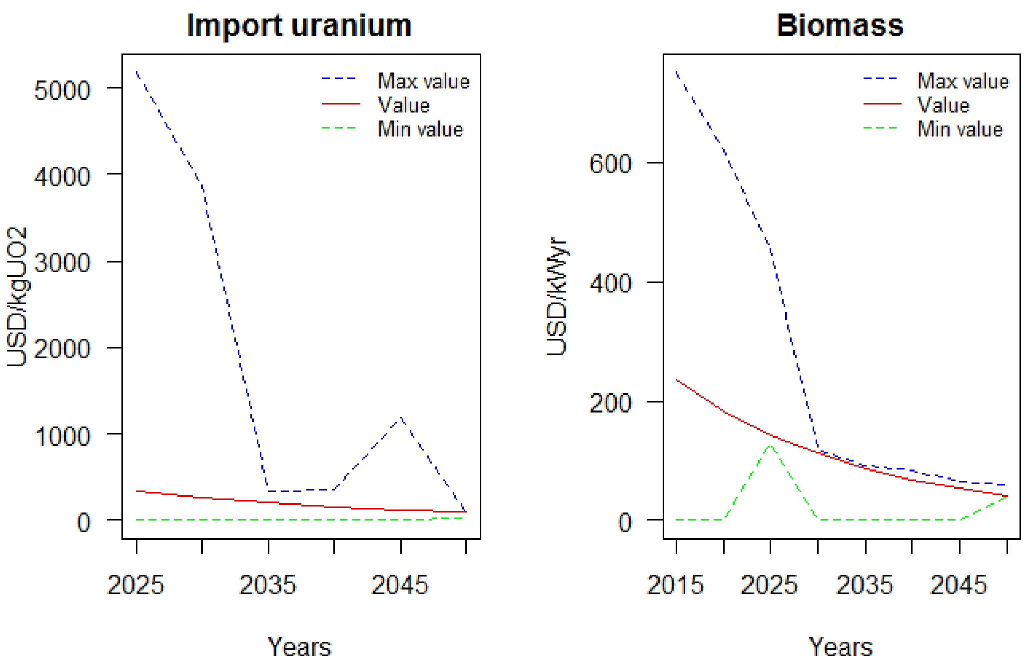

Figure 3.117: Low carbon fuel costs for RCP2.6 in SSP2

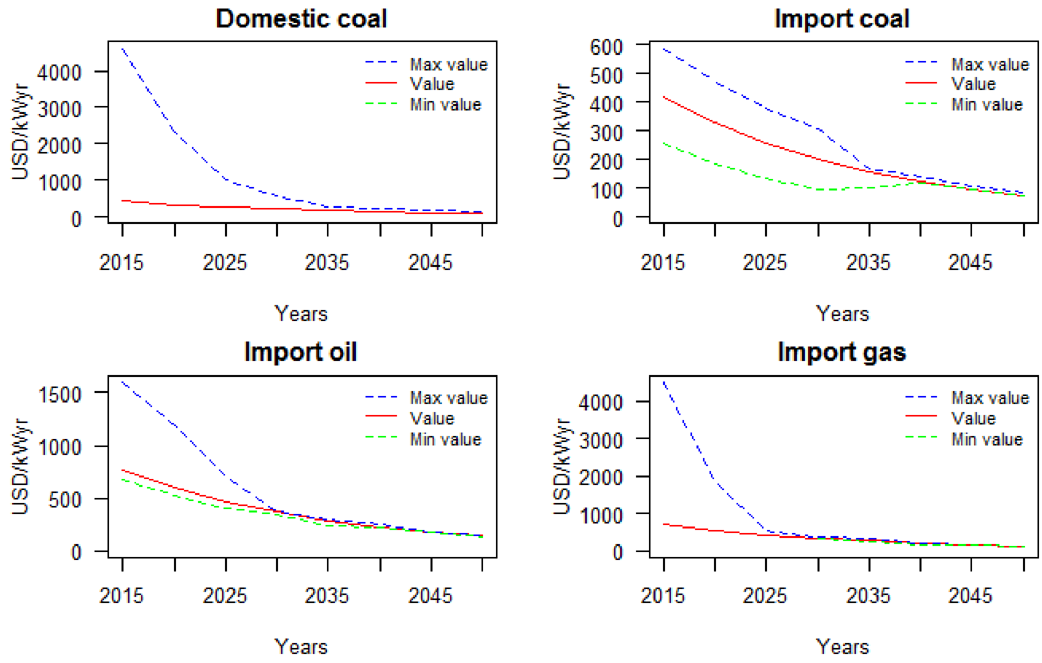

Figure 3.118: Primary fossil fuel costs for Baseline in SSP3

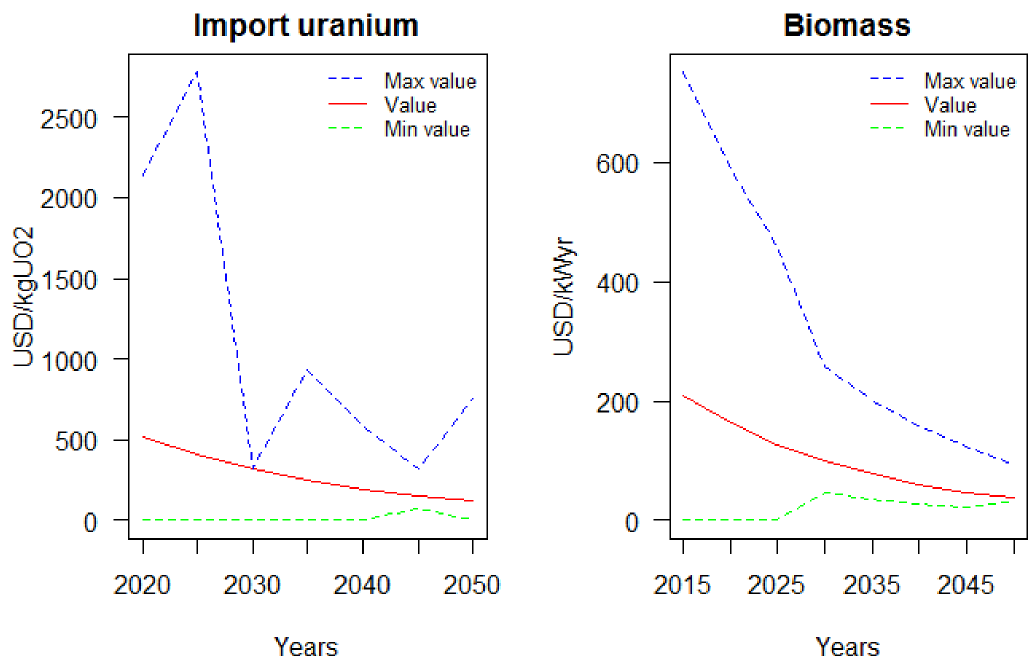

Figure 3.119: Low carbon fuel costs for Baseline in SSP3

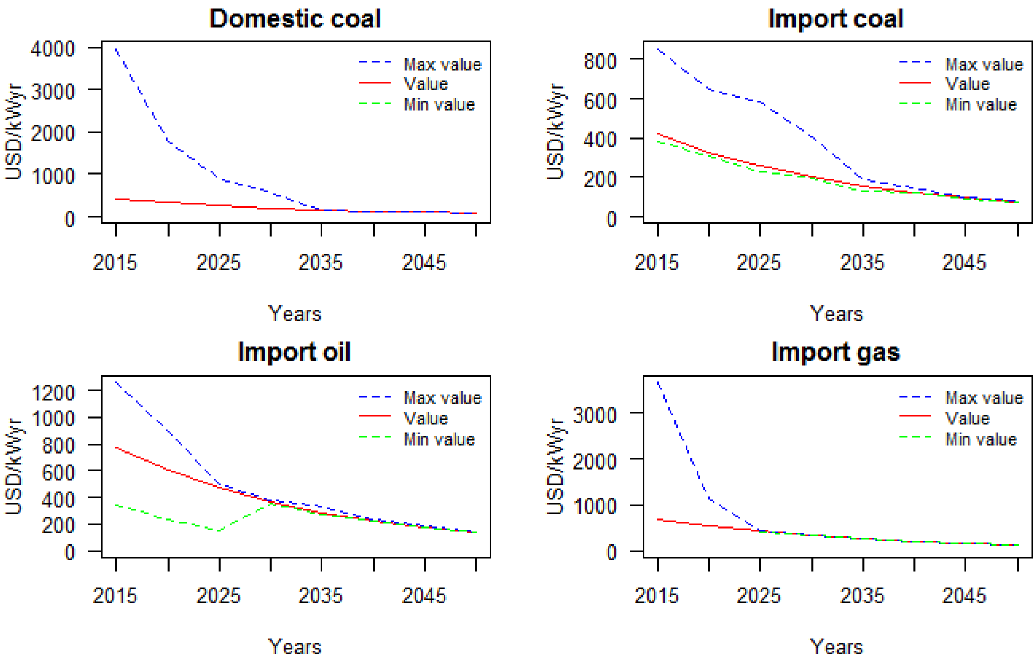

Figure 3.120: Primary fossil fuel costs for RCP3.4 in SSP3

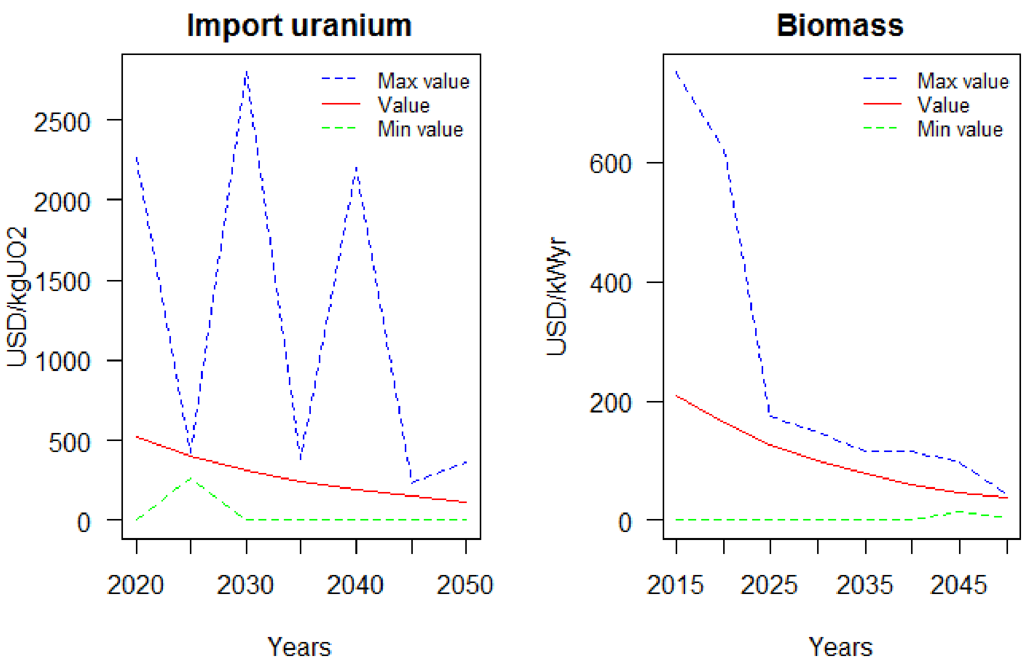

Figure 3.121: Low carbon fuels for RCP3.4 in SSP3

for continued operation. The results of the modeling study shows that the penetration of nuclear energy is high for Baseline scenarios in all SSPs independently from the increase in final energy demand. Implementing CO_2 penalty tax on fossil fuel resources and usage of these revenues for investment in renewable energy resources reduces the robustness of the electricity grid to supply peak load demand. Therefore we can reject Hypothesis I as the grid requirements are important and nuclear energy could take advantage by using flexible generation operation schemes.

The marginal costs of electricity generation are highest in the initial years of the modeling horizon due to the non-optimal allocation of resources in relation to the costs of energy conversion technologies. The optimization solver calculates the energy system expansion to supply the final energy demand under technical and environmental constraints. The marginal costs increase for all scenarios in 2035 where the operation lifetimes of installed capacities expire leaving the way for low carbon energy investments. Under the renewable support scheme with FITs, the model prioritizes the allocation of wind and solar power on the expense of grid flexibility. The most stringent climate target scenarios include limited expansion of nuclear energy leading to the rejection of Hypothesis II.

The FITs using revenues collected from CO_2 emission penalty costs provide both a subsidy for electricity generation from renewable energy resources and also an upper constraint as the total budget available is fixed. The high penetration of renewable energy would also result in reduction of this revenue which would lead to non-optimal energy system development under carbon emission constraint. Developing countries rely on diffusion and spillover of technological innovations requiring their large deployment primarily in developed countries. We can accept Hypothesis III as nuclear energy is included in all climate scenarios with high flexibility and also could benefit the most stringent climate targets with flexible operation schemes.

The energy policy decisions of Turkey are based on the strengthening of energy security with reduction of energy system costs. However the market mechanism for energy investments requires increasing marginal prices which would result mainly from increase in final energy demand. Nuclear energy is perceived as highly important similarly to other low carbon energy sources including intermittent renewable energy resources. The importance given to domestic coal is highest among fossil fuel resources although this importance is under the low carbon resources. Therefore we can reject Hypothesis IV as high importance is given to both climate mitigation and energy security by energy experts.

Finally as the target is to reduce GHG emissions in order to limit the extent of climate change and achieve the most stringent climate goals, the resulting CO_2 emission intensities of production are presented in Figure 3.122 for SSPs with IAM results of energy efficiency improvements on the vertical scale. The results show that providing low carbon energy technologies and internalizing the costs of CO_2 emissions are not sufficient to reduce the carbon intensity of production and additional mitigation measures for non-specific energy demand are necessary (such as using higher efficiency industrial boilers, fuel switching, transformation of transport sector).

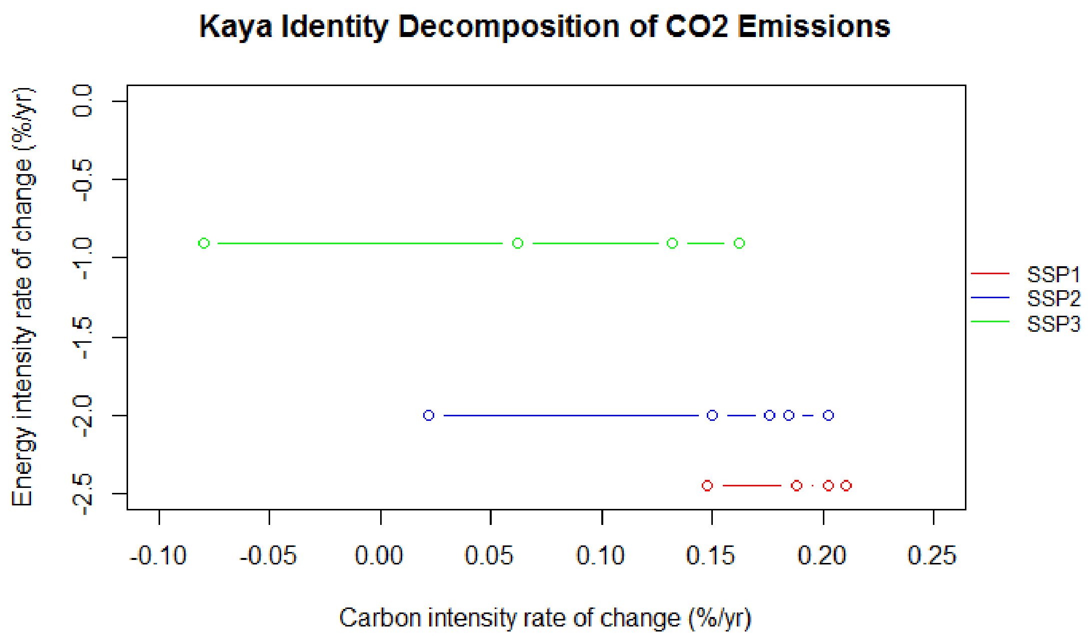

Figure 3.122: Energy and carbon intensity change for SSPs (%/yr)

CHAPTER 4

DISCUSSION AND CONCLUSION

The results presented below provide a foresight for the second commitment period of the Paris Agreement until 2050. Final energy demand is included exogenously to the model for baseline scenarios and mitigation scenarios include additional costs for CO_2 emissions. Climate mitigation technologies are hydropower, biomass, wind, solar and geothermal for secondary electricity generation and biodiesel for final diesel demand.

The mathematical model used in this study calculates the minimized total energy system costs under economical, environmental and social constraints. Baseline scenarios include only penalty costs for air pollutant emissions of SO_2 and NO_x. The mitigations scenarios used for reducing the cumulative carbon emissions include penalty costs for CO_2 emissions based on IAM results of SSPs.

Energy security is represented by the flexibility of the electricity grid to supply peak load on demand. Fossil power plants and NPPs have technological constraints for period required to ramp up or ramp down power generation whereas renewable energy sources are intermittent and require balancing with base load electricity generation. Finally the revenues collected from emission penalties are provided as FITs for solar, geothermal and biomass power plants to subsidize their high capital costs. The marginal costs of electricity generation with FITs represent welfare loss which is used as additional criteria for minimization.

The expert elicitation survey uses Likert scale reflecting the importance given to climate change mitigation and energy security strategies. Climate change is perceived with high importance whereas energy security is also perceived as important for sustainable development. Primary strategy for climate mitigation is the increasing usage of renewable energy sources such as wind and solar power. Wind power is already utilized at large scale in both onshore and offshore power plants and the capital cost of solar power is decreasing at a fast rate increasing the market penetration of PV technology. Extended usage of these renewable sources requires additional subsidies to geothermal and biomass power technologies for their market penetration.

The results are provided in radar plots for MCA objectives used for scenario assessment in this study. The most stringent climate scenario in SSP1 has highest values for CO_2 emissions and subsidies for electricity generation from renewable energy sources by using FITs from emission penalty costs (Figure 4.1). The baseline scenario provides the highest flexibility of electricity grid to supply peak load demand and minimum total discounted energy system cost.

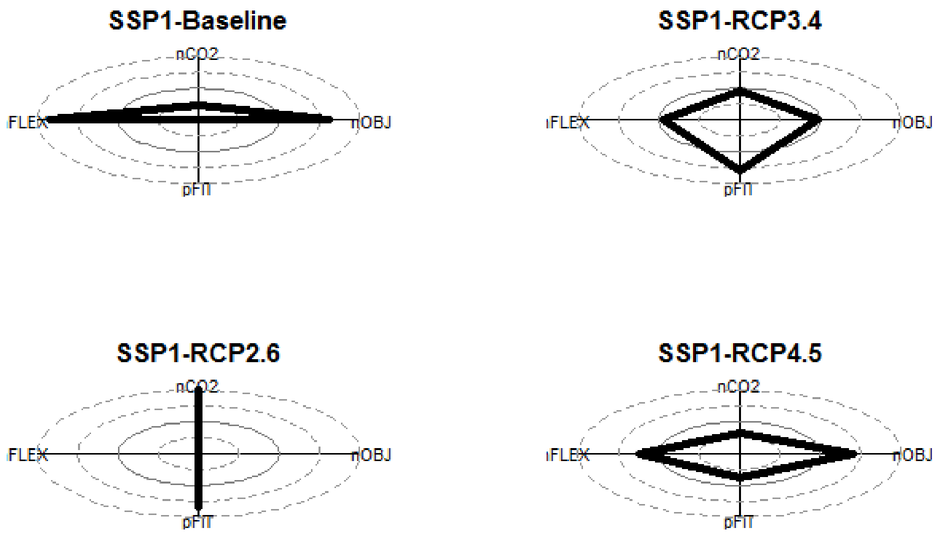

Figure 4.1: MCA of SSP1 scenarios

The results for SSP2 provides that reductions in CO_2 emissions are minor in scenarios except RCP2.6 in the expense of reduction in grid flexibility to supply peak load demand and increasing total discounted energy system cost (Figure 4.2). Also the increase of climate ambition from RCP6.0 to RCP4.5 results in minor changes in

MCA values leaving the remaining scenarios for consideration.

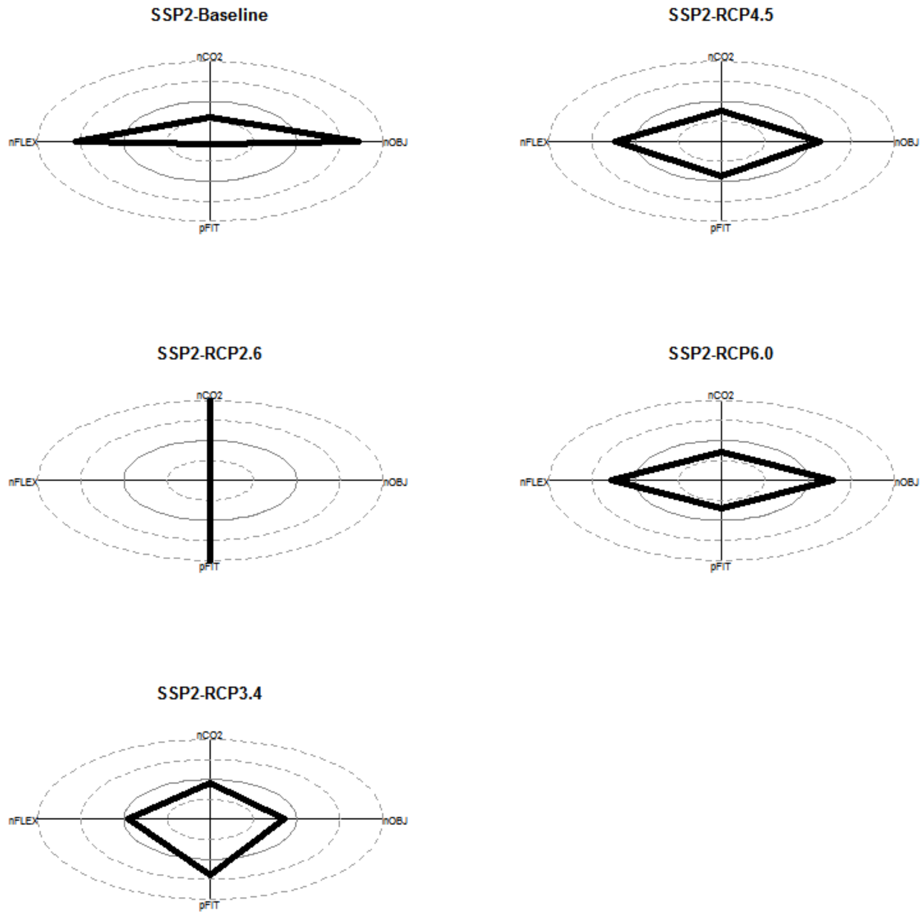

Figure 4.2: MCA of SSP2 scenarios

Increasing the climate ambition in SSP3 results in minor reduction in CO_2 for all scenarios except RCP3.4 (Figure 4.3). Also the increase of climate ambition from RCP6.0 to RCP4.5 results mainly in the increase of total discounted energy system cost leaving other MCA values close to each other.

Using the weights from the expert elicitation study for the MCA values provides the ranking of RCP scenarios for SSPs. The SSPs are differentiated by the level of final energy demand with the lowest represented by SSP1 and the highest by SSP3 due to socioeconomic assumptions. The application of weights for MCA values in SSPs results in ranking of scenarios as listed below.

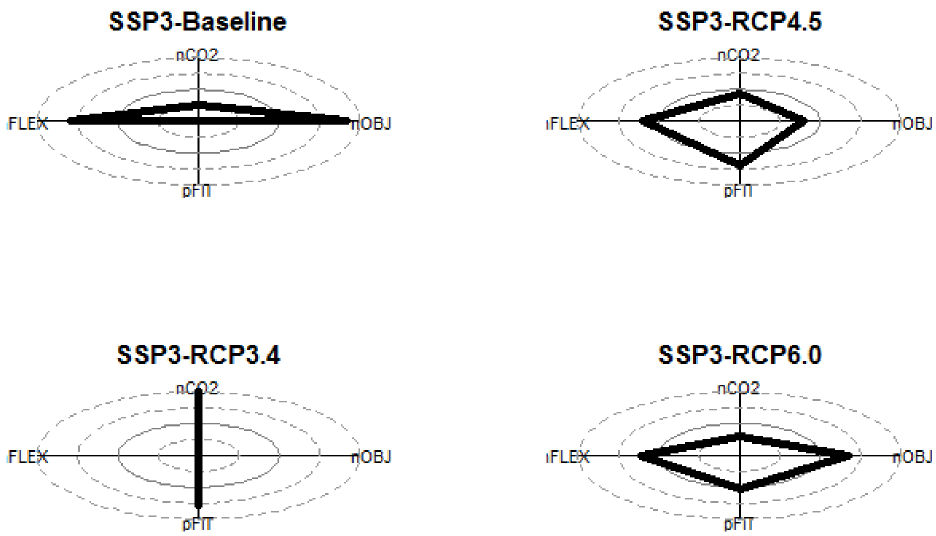

Figure 4.3: MCA of SSP3 scenarios

- SSP1 scenarios
  - Rank 1: RCP3.4
  - Rank 2: Baseline
  - Rank 3: RCP4.5
  - Rank 4: RCP2.6
- SSP2 scenarios
  - Rank 1: RCP3.4
  - Rank 2: RCP4.5
  - Rank 3: RCP6.0
  - Rank 4: Baseline
  - Rank 5: RCP2.6
- SSP3 scenarios
  - Rank 1: RCP4.5

- Rank 2: RCP3.4
- Rank 3: RCP6.0
- Rank 4: Baseline

Primary energy demand for fossil energy resources (Table 4.2) shows increasing demand for both domestic and imported coal and imported natural gas and crude oil as energy demand increases. Crude oil is processed in domestic refineries for production of oil products. The import oil products mainly constitute petrocoke required for final energy demand.

Table 4.1: Primary fossil energy demand (GW-year) in 2035

Energy demand	Domestic coal	Import coal	Natural gas	Crude oil	Oil products
Low	40.32	22.74	65.29	49.88	2.44
Medium	40.48	22.64	64.01	51.86	2.53
High	40.48	21.97	75.76	59.48	3.12

Table 4.2: Primary fossil energy demand (GW-year) in 2050

Energy demand	Domestic coal	Import coal	Natural gas	Crude oil	Oil products
Low	34.19	22.49	64.05	52.90	2.42
Medium	35.80	22.51	61.34	56.47	2.62
High	39.70	21.74	58.52	65.05	3.40

Primary energy demand for renewable energy sources 4.4 shows increasing demand for hydropower, biomass and geothermal as energy demand increases. Hydropower is also utilized to achieve flexibility requirements of electricity transmission grid to supply peak load electricity by storing capability. Biomass and geothermal are used for both electricity generation and also heating purposes. There is also a climate mitigation technology for biodiesel production using primary biomass. Wind and solar have input load regions defined in the model in order to define them as complementary technologies. Availability of solar is maximum during daytime and wind during morning and evening times due to most of capacity lying on the western Aegean coast affected by temperature changes between sea and land.

Results for installed capacity for electricity generation 4.6 shows that nuclear energy

Table 4.3: Primary renewable energy demand (GW-year) in 2035

Energy demand	Hydropower	Biomass	Wind	Solar	Geothermal
Low	5.98	1.83	1.73	5.21	2.25
Medium	5.94	2.00	1.86	6.07	2.32
High	6.05	2.48	1.71	6.34	2.64

Table 4.4: Primary renewable energy demand (GW-year) in 2050

Energy demand	Hydropower	Biomass	Wind	Solar	Geothermal
Low	5.23	1.64	6.18	6.39	1.97
Medium	5.11	1.86	8.18	9.75	2.17
High	4.76	2.51	13.93	18.08	2.68

has a potential role for climate mitigation in medium and high baseline scenarios together with renewable energy. Low baseline scenario requires a major paradigm shift which results in saturation of final energy demand favouring intensive penetration of wind and solar with concerns to achieve grid flexibility requirements.

Table 4.5: Installed low carbon electricity capacity (GW) in 2035

Energy demand	Nuclear	Hydro	Wind	Solar	Geothermal	Biomass
Low	0	25.73	10.83	18.92	0.41	0.33
Medium	0	25.73	11.65	24.21	0.41	0.36
High	4.00	25.83	10.73	21.06	0.43	0.36

In order to achieve the most stringent climate targets, additional climate and energy policies besides subsidizing low carbon investments should be used for the reduction of carbon intensity of production. Substitution of fossil fuels in final energy demand are important especially for carbon intensive sectors such as cement and steel production and also transportation sector. Long term climate mitigation strategies could benefit from extended utilization of nuclear energy for substitution of fossil fuels for final energy demand such as process heat and hydrogen production besides electricity generation.

Table 4.6: Installed low carbon electricity capacity (GW) in 2050

Energy demand	Nuclear	Hydro	Wind	Solar	Geothermal	Biomass
Low	5.00	21.23	29.17	15.42	0.19	0.09
Medium	2.00	20.73	40.93	35.76	0.19	0.17
High	4.00	20.73	77.97	85.92	0.21	0.17

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APPENDIX A

MESSAGE CODE FOR ENERGY SYSTEM MODELING

```
tdb: empty
adb: Turkey
problem: Turkey
description:
# TR
# Baseline scenario using SSP3 and GEA-Supply scenario parameters
drate: 5.04
timesteps: 2014 2015 2020 2025 2030 2035 2040 2045 2050 2055
loadregions:
ltype        ordered seasonal 1 0
year        2015 1 60
name         aaa aab aac \
         aba abb \
         baa bab bac \
         bba bbb \
         caa cab cac \
         cba cbb \
         daa dab dac \
         dba dbb \
         eaa eab eac \
         eba ebb \
         faa fab fac \
         fba fbb \
         gaa gab gac \
         gba gbb \
         haa hab hac \
         hba hbb \
```

```
         iaa iab iac \
         iba ibb \
         jaa jab jac \
         jba jbb \
         kaa kab kac \
         kba kbb \
         laa lab lac \
         lba lbb
length         0.015068 0.030137 0.015068 \
         0.012329 0.012329 \
         0.013699 0.027397 0.013699 \
         0.010959 0.010959 \
         0.015068 0.030137 0.015068 \
         0.012329 0.012329 \
         0.015068 0.030137 0.015068 \
         0.010959 0.010959 \
         0.014384 0.028767 0.014384 \
         0.013699 0.013699 \
         0.015068 0.030137 0.015068 \
         0.010959 0.010959 \
         0.015753 0.031507 0.015753 \
         0.010959 0.010959 \
         0.014384 0.028767 0.014384 \
         0.013699 0.013699 \
         0.015068 0.030137 0.015068 \
         0.010959 0.010959 \
         0.015068 0.030137 0.015068 \
         0.012329 0.012329 \
         0.014384 0.028767 0.014384 \
         0.012329 0.012329 \
         0.015753 0.031507 0.015753 \
         0.010959 0.010959
energyforms:
NUCLEAR N
# Nuclear energy
    LWR_fuel w
    # LWR fuel
```

```
    SWU s
    # Seperative work unit
    U_en u
    # Enriched uranium
    Uranium r
    # Natural uranium
*
FINAL F
# Final energy
    Electricity e l
    # Final electricity
    Coke o
    # Final coke
    Petro_coke p
    # Final petroleum coke
    Coal c
    # Final coal
    Fuel_oil f
    # Final fuel oil
    Diesel d
    # Final diesel
    Gasoline g
    # Final gasoline
    Kerosene j
    # Final jet-fuel
    Feedstock b
    # Final petrochemical feedstock
    Gas a l
    # Final gas
    Residential_heat s l
    # Final residential hear
    Biomass i
    # Final biomass
    Process_heat t l
    # Final process heat
    LPG l
    # Final LPG
```

```
*
SECONDARY S
# Secondary energy
    Electricity e l
    # Secondary electricity
*
PRIMARY P
# Primary energy
    Coal_Dom c
    # Domestic coal
    Coal_Imp l
    # Imported hard coal
    Oil o
    # Primary oil
    Gas g
    # Primary gas
    Biomass b
    # Primary biomass
    Solar s l
    # Primary solar
    Geothermal e
    # Primary geothermal
    Wind w l
    # Primary wind
*
RESOURCES R
# Energy resources
    Coal_Dom c
    # Domestic coal
    Lignite l
    # Domestic lignite
*
DUMMY D
# Dummy energy
    LWR_cool l
    # Spent fuel in final core
    LWR_dummy k
```

```
    # Spent fuel transfer
    Oil_dummy o
    # Oil refinery output
*
demand:
i-F pg 1311 1.0339 1.0227 1.0149 1.0099 1.0079 1.0058 1.0043 1.0043
c-F pg 13591 1.0339 1.0227 1.0149 1.0099 1.0079 1.0058 1.0043 1.0043
o-F pg 3886 1.0339 1.0227 1.0149 1.0099 1.0079 1.0058 1.0043 1.0043
d-F pg 11497 1.0339 1.0227 1.0149 1.0099 1.0079 1.0058 1.0043 1.0043
e-F pg 23723 1.0382 1.027 1.0191 1.0142 1.0122 1.0101 1.0085 1.0085
b-F pg 5869 1.0329 1.0217 1.0138 1.0089 1.0069 1.0048 1.0033 1.0033
f-F pg 4849 1.0339 1.0227 1.0149 1.0099 1.0079 1.0058 1.0043 1.0043
a-F pg 28809 1.0339 1.0227 1.0149 1.0099 1.0079 1.0058 1.0043 1.0043
g-F pg 6804 1.0339 1.0227 1.0149 1.0099 1.0079 1.0058 1.0043 1.0043
j-F pg 6687 1.0339 1.0227 1.0149 1.0099 1.0079 1.0058 1.0043 1.0043
l-F pg 1838 1.0339 1.0227 1.0149 1.0099 1.0079 1.0058 1.0043 1.0043
p-F pg 3835 1.0339 1.0227 1.0149 1.0099 1.0079 1.0058 1.0043 1.0043
t-F pg 1570 1.0339 1.0227 1.0149 1.0099 1.0079 1.0058 1.0043 1.0043
s-F pg 3050 1.0339 1.0227 1.0149 1.0099 1.0079 1.0058 1.0043 1.0043
loadcurve:
year 2015
relations2.1river.1riv.upper 0.126465 0.160955 0.095806 0.111310 0.078387 \
    0.028286 0.036000 0.021429 0.024343 0.017143 0.079626 \
    0.101342 0.060323 0.070084 0.049355 0.023627 0.030378 \
    0.030378 0.015562 0.010959 0.022554 0.028997 0.028997 \
    0.019452 0.013699 0.023627 0.030378 0.030378 0.015562 \
    0.010959 0.024702 0.031759 0.031759 0.015562 0.010959 \
    0.022554 0.028997 0.028997 0.019452 0.013699 0.023627 \
    0.030378 0.030378 0.015562 0.010959 0.023628 0.030378 \
    0.030378 0.017507 0.012329 0.022553 0.028997 0.028997 \
    0.017507 0.012329 0.024702 0.031759 0.031759 0.015562 \
    0.010959
e-F 0.012135 0.034490 0.017245 0.011758 0.014371 \
```

```
    0.010857 0.030857 0.015429 0.010743 0.012114 0.010787 \
    0.030658 0.015329 0.010684 0.012542 0.011733 0.031093 \
    0.015840 0.010240 0.011093 0.010839 0.028723 0.014632 \
    0.011871 0.013935 0.011733 0.031680 0.015253 0.010027 \
    0.011307 0.014023 0.034723 0.018029 0.010916 0.012310 \
    0.012194 0.032923 0.015852 0.013645 0.015387 0.011733 \
    0.031680 0.015253 0.009813 0.011520 0.011355 0.030658 \
    0.014761 0.010916 0.012310 0.011200 0.029680 0.015120 \
    0.011280 0.012720 0.013355 0.036058 0.017361 0.010684 \
    0.012542
relations2.2river.2riv.upper 0.015069 0.030137 0.015069 0.012329
 ↪  0.012329 \
    0.013699 0.027397 0.013699 0.010959 0.010959 0.015069 \
    0.030137 0.015069 0.012329 0.012329 0.015069 0.030137 \
    0.015069 0.010959 0.010959 0.014384 0.028767 0.014384 \
    0.013699 0.013699 0.015069 0.030137 0.015069 0.010959 \
    0.010959 0.015754 0.031507 0.015754 0.010959 0.010959 \
    0.014384 0.028767 0.014384 0.013699 0.013699 0.015069 \
    0.030137 0.015069 0.010959 0.010959 0.015069 0.030137 \
    0.015069 0.012329 0.012329 0.014384 0.028767 0.014384 \
    0.012329 0.012329 0.015754 0.031507 0.015754 0.010959 \
    0.010959
a-F 0.021290 0.042581 0.021290 0.017419 0.017419 \
    0.017857 0.035714 0.017857 0.014286 0.014286 0.015968 \
    0.031935 0.015968 0.013065 0.013065 0.014667 0.029333 \
    0.014667 0.010667 0.010667 0.011855 0.023710 0.011855 \
    0.011290 0.011290 0.011000 0.022000 0.011000 0.008000 \
    0.008000 0.011129 0.022258 0.011129 0.007742 0.007742 \
    0.010161 0.020323 0.010161 0.009677 0.009677 0.014667 \
    0.029333 0.014667 0.010667 0.010667 0.014194 0.028387 \
    0.014194 0.011613 0.011613 0.015750 0.031500 0.015750 \
    0.013500 0.013500 0.020403 0.040806 0.020403 0.014194 \
    0.014194
relations2.1river.1riv.outflow 0.015069 0.030137 0.015069
 ↪  0.012329 0.012329 \
    0.013699 0.027397 0.013699 0.010959 0.010959 0.015069 \
    0.030137 0.015069 0.012329 0.012329 0.015069 0.030137 \
```

```
    0.015069 0.010959 0.010959 0.014384 0.028767 0.014384 \
    0.013699 0.013699 0.015069 0.030137 0.015069 0.010959 \
    0.010959 0.015754 0.031507 0.015754 0.010959 0.010959 \
    0.014384 0.028767 0.014384 0.013699 0.013699 0.015069 \
    0.030137 0.015069 0.010959 0.010959 0.015069 0.030137 \
    0.015069 0.012329 0.012329 0.014384 0.028767 0.014384 \
    0.012329 0.012329 0.015754 0.031507 0.015754 0.010959 \
    0.010959
relations2.2river.2riv.inflow 0.017742 0.035484 0.017742 0.014516 0.014516 \
    0.021429 0.042857 0.021429 0.017143 0.017143 0.021290 \
    0.042581 0.021290 0.017419 0.017419 0.025667 0.051333 \
    0.025667 0.018667 0.018667 0.018629 0.037258 0.018629 \
    0.017742 0.017742 0.007333 0.014667 0.007333 0.005333 \
    0.005333 0.001855 0.003710 0.001855 0.001290 0.001290 \
    0.001694 0.003387 0.001694 0.001613 0.001613 0.003667 \
    0.007333 0.003667 0.002667 0.002667 0.017742 0.035484 \
    0.017742 0.014516 0.014516 0.021000 0.042000 0.021000 \
    0.018000 0.018000 0.020403 0.040806 0.020403 0.014194 \
    0.014194
relations2.1river.1riv.inflow 0.017742 0.035484 0.017742 0.014516 0.014516 \
    0.021429 0.042857 0.021429 0.017143 0.017143 0.021290 \
    0.042581 0.021290 0.017419 0.017419 0.025667 0.051333 \
    0.025667 0.018667 0.018667 0.018629 0.037258 0.018629 \
    0.017742 0.017742 0.007333 0.014667 0.007333 0.005333 \
    0.005333 0.001855 0.003710 0.001855 0.001290 0.001290 \
    0.001694 0.003387 0.001694 0.001613 0.001613 0.003667 \
    0.007333 0.003667 0.002667 0.002667 0.017742 0.035484 \
    0.017742 0.014516 0.014516 0.021000 0.042000 0.021000 \
    0.018000 0.018000 0.020403 0.040806 0.020403 0.014194 \
    0.014194
relations2.1river.1riv.lower 0.015069 0.030137 0.015069 0.012329 0.012329 \
    0.013699 0.027397 0.013699 0.010959 0.010959 0.015069 \
    0.030137 0.015069 0.012329 0.012329 0.015069 0.030137 \
    0.015069 0.010959 0.010959 0.014384 0.028767 0.014384 \
```

```
    0.013699 0.013699 0.015069 0.030137 0.015069 0.010959 \
    0.010959 0.015754 0.031507 0.015754 0.010959 0.010959 \
    0.014384 0.028767 0.014384 0.013699 0.013699 0.015069 \
    0.030137 0.015069 0.010959 0.010959 0.015069 0.030137 \
    0.015069 0.012329 0.012329 0.014384 0.028767 0.014384 \
    0.012329 0.012329 0.015754 0.031507 0.015754 0.010959 \
    0.010959
systems.Solar.x.moutp 0.015968 0.031935 0.015968 0.013065
 ↪  0.013065 \
    0.016071 0.032143 0.016071 0.012857 0.012857 0.015968 \
    0.031935 0.015968 0.013065 0.013065 0.014667 0.029333 \
    0.014667 0.010667 0.010667 0.013548 0.027097 0.013548 \
    0.012903 0.012903 0.014667 0.029333 0.014667 0.010667 \
    0.010667 0.014839 0.029677 0.014839 0.010323 0.010323 \
    0.013548 0.027097 0.013548 0.012903 0.012903 0.014667 \
    0.029333 0.014667 0.010667 0.010667 0.014194 0.028387 \
    0.014194 0.011613 0.011613 0.014000 0.028000 0.014000 \
    0.012000 0.012000 0.016694 0.033387 0.016694 0.011613 \
    0.011613
systems.Solar.a.moutp 0.000000 0.063871 0.000000 0.026129
 ↪  0.000000 \
    0.000000 0.064286 0.000000 0.025714 0.000000 0.000000 \
    0.063871 0.000000 0.026129 0.000000 0.000000 0.058667 \
    0.000000 0.021333 0.000000 0.000000 0.054194 0.000000 \
    0.025806 0.000000 0.000000 0.058667 0.000000 0.021333 \
    0.000000 0.000000 0.059355 0.000000 0.020645 0.000000 \
    0.000000 0.054194 0.000000 0.025806 0.000000 0.000000 \
    0.058667 0.000000 0.021333 0.000000 0.000000 0.056774 \
    0.000000 0.023226 0.000000 0.000000 0.056000 0.000000 \
    0.024000 0.000000 0.000000 0.066774 0.000000 0.023226 \
    0.000000
t-F 0.015069 0.030137 0.015069 0.012329 0.012329 \
    0.013699 0.027397 0.013699 0.010959 0.010959 0.015069 \
    0.030137 0.015069 0.012329 0.012329 0.015069 0.030137 \
    0.015069 0.010959 0.010959 0.014384 0.028767 0.014384 \
    0.013699 0.013699 0.015069 0.030137 0.015069 0.010959 \
    0.010959 0.015754 0.031507 0.015754 0.010959 0.010959 \
```

```
    0.014384 0.028767 0.014384 0.013699 0.013699 0.015069 \
    0.030137 0.015069 0.010959 0.010959 0.015069 0.030137 \
    0.015069 0.012329 0.012329 0.014384 0.028767 0.014384 \
    0.012329 0.012329 0.015753 0.031506 0.015753 0.010958 \
    0.010958
systems.Wind.a.moutp 0.028387 0.000000 0.028387 0.000000 0.023226 \
    0.032143 0.000000 0.032143 0.000000 0.025714 0.028387 \
    0.000000 0.028387 0.000000 0.023226 0.029333 0.000000 \
    0.029333 0.000000 0.021333 0.027097 0.000000 0.027097 \
    0.000000 0.025806 0.033000 0.000000 0.033000 0.000000 \
    0.024000 0.033387 0.000000 0.033387 0.000000 0.023226 \
    0.030484 0.000000 0.030484 0.000000 0.029032 0.029333 \
    0.000000 0.029333 0.000000 0.021333 0.028387 0.000000 \
    0.028387 0.000000 0.023226 0.028000 0.000000 0.028000 \
    0.000000 0.024000 0.029677 0.000000 0.029677 0.000000 \
    0.020645
s-F 0.021290 0.042581 0.021290 0.017419 0.017419 \
    0.017857 0.035714 0.017857 0.014286 0.014286 0.015968 \
    0.031935 0.015968 0.013065 0.013065 0.014667 0.029333 \
    0.014667 0.010667 0.010667 0.011855 0.023710 0.011855 \
    0.011290 0.011290 0.011000 0.022000 0.011000 0.008000 \
    0.008000 0.011129 0.022258 0.011129 0.007742 0.007742 \
    0.010161 0.020323 0.010161 0.009677 0.009677 0.014667 \
    0.029333 0.014667 0.010667 0.010667 0.014194 0.028387 \
    0.014194 0.011613 0.011613 0.015750 0.031500 0.015750 \
    0.013500 0.013500 0.020403 0.040806 0.020403 0.014194 \
    0.014194
relations2.2river.2riv.lower 0.015068 0.030137 0.015068 0.012329
↪   0.012329 \
    0.013699 0.027397 0.013699 0.010959 0.010959 0.015068 \
    0.030137 0.015068 0.012329 0.012329 0.015068 0.030137 \
    0.015068 0.010959 0.010959 0.014384 0.028767 0.014384 \
    0.013699 0.013699 0.015068 0.030137 0.015068 0.010959 \
    0.010959 0.015753 0.031507 0.015753 0.010959 0.010959 \
    0.014384 0.028767 0.014384 0.013699 0.013699 0.015068 \
    0.030137 0.015068 0.010959 0.010959 0.015068 0.030137 \
    0.015068 0.012329 0.012329 0.014384 0.028767 0.014384 \
```

```
    0.012329 0.012329 0.015753 0.031507 0.015753 0.010959 \
    0.010959
costlims:
investments lo annual c 0
relations1 lo annual c 0
relationsc:
FIT FIT o
    cost        c -1165
    units        group: activity, type: energy, cost:US$'00/kWyr,
     ↪  upper:MWyr, lower:MWyr
    for_ldr        none
    upper        c 32918
    lower        c 0
    type        None
*
relationsp:
relationss:
1stor 1sto o 0
    units        type: energy, cost:US$'00/kWyr, inv:US$'00/kW,
     ↪  fom:US$'00/kW/yr, pll:yr, cmix:MW, hisccap:MW, ctime:yr,
     ↪  reten:yr, retenhist:MWyr, upper:MWyr, lower:MWyr
    for_ldr        all
    upper        c 6800
    lower        c 0
    stortype        continuous
    type        hydro
    inflow        p1riv        c 1
    overflow        pnone        c 1.
*
2stor 2sto o 0
    units        type: energy, cost:US$'00/kWyr, inv:US$'00/kW,
     ↪  fom:US$'00/kW/yr, pll:yr, cmix:MW, hisccap:MW, ctime:yr,
     ↪  reten:yr, retenhist:MWyr, upper:MWyr, lower:MWyr,
     ↪  transfac:%
    for_ldr        all
    upper        c 18200
    lower        c 0
```

```
    stortype        continuous
    type        hydro
    inflow        p2riv        c 1
    overflow        pnone        c 1.
*
LWR_cool_st q o
    cost        c 5
    units        type: energy, cost:US$'00/kWyr, inv:US$'00/kW,
     ↪  fom:US$'00/kW/yr, pll:yr, cmix:MWyr, hisccap:MWyr,
     ↪  ctime:yr, reten:yr, retenhist:MWyr, upper:MWyr,
     ↪  lower:MWyr, transfac:%
    for_ldr        none
    reten        c 5
    upper        c 1000
    lower        c 0
    stortype        continuous
    type        None
*
L_int_stor L_in o
    cost        c 200
    units        type: energy, cost:US$'00/kWyr, inv:US$'00/kW,
     ↪  fom:US$'00/kW/yr, pll:yr, cmix:MWyr, hisccap:MWyr,
     ↪  ctime:yr, reten:yr, retenhist:MWyr, upper:MWyr,
     ↪  lower:MWyr, transfac:%
    for_ldr        none
    upper        c 10000
    lower        c 0
    stortype        continuous
    type        None
*
depleted_U_st depl o
    units        type: energy, cost:US$'00/kWyr, inv:US$'00/kW,
     ↪  fom:US$'00/kW/yr, pll:yr, cmix:MWyr, hisccap:MWyr,
     ↪  ctime:yr, reten:yr, retenhist:MWyr, lower:MWyr, transfac:%
    for_ldr        none
    lower        c 0
    stortype        continuous
```

```
    type        None
*
LILW_stor LILW o
    cost        c 8.05
    units        type: energy, cost:US$'00/kWyr, inv:US$'00/kW, fom:US$'00/kW/yr, pll:yr, cmix:MWyr, hisccap:MWyr, ctime:yr, reten:yr, retenhist:MWyr, upper:MWyr, lower:MWyr, transfac:%
    for_ldr        none
    lower        c 0
    stortype        continuous
    type        None
*
relations1:
CO2 CO2 o
    units        group: activity, type: weight, upper:kton, lower:kton
    for_ldr        none
    lower        c 0
    type        None
*
NOx NOx o
    cost        c 1750
    units        group: activity, type: weight, cost:EUR'00/ton, upper:kton, lower:kton
    for_ldr        none
    lower        c 0
    type        None
*
SO2 SO2 o
    cost        c 480
    units        group: activity, type: weight, cost:EUR'00/ton, upper:kton, lower:kton
    for_ldr        none
    lower        c 0
*
FLEX FLEX o 0
```

```
    units        group: activity, type: energy, cost:US$'00/kWyr, upper:MWyr, lower:MWyr
    for_ldr        all
    lower        c 0
    type        None
*
relations2:
1river 1riv o 0
    units        group: activity, type: energy, cost:US$'00/kWyr, upper:MWyr, lower:MWyr
    for_ldr        all
    lower        c 0.
    type        river
    inflow        pnatural        c 6800
    outflow        pnatural        c 1
*
2river 2riv o 0
    units        group: activity, type: energy, cost:US$'00/kWyr, upper:MWyr, lower:MWyr
    for_ldr        all
    lower        c 0
    type        river
    inflow        pnatural        c 11400
    outflow        pnatural        c 1
*
variables:
systems:
Elec_S_F a
    minp        e-S 1.
    moutp        e-F c 0.82
    pll        c 50
    inv        c 118
    fom        c 4.83
```

```
    hisc        23723.        hc 1970 985 1971 131 1972 167 1973
     ↪  135 1974 119 1975 245 1976 228 1977 197 1978 131 1979 91
     ↪  1980 86 1981 159 1982 213 1983 91 1984 373 1985 411 1986
     ↪  471 1987 531 1988 422 1989 456 1990 627 1991 308 1992 809
     ↪  1993 738 1994 516 1995 904 1996 983 1997 962 1998 882
     ↪  1999 618 2000 967 2002 511 2003 1277 2004 1155 2005 1643
     ↪  2006 1638 2007 1741 2008 783 2010 1460 2011 2076 2012
     ↪  1153 2013 74 2014 1348
    ctime        c 2
    con1a FLEX        c -0.1
#
*
Gas_TD a
    minp        g-P 1.
    moutp        a-F c 1
    hisc        28809.
    con1a CO2        c 1.77
#
*
Nuclear_PP a
    minp        w-N 0.017885000000000002
    moutp        e-S c 1
    plf        c 0.85
    pll        c 60
    inv        ts 5211 4977 4977 4747 4747 4460 4460 4184 4184
    fom        ts 153 145 145 139 139 129 129 122 122
    vom        c 26.28
    cmix        2 1000
    ctime        c 5
    bdc up        c 1000
    corin w-N        c 0.054047
    corout l-D        c 0.054047
    con1a CO2        c 0.569
    consa q        c 0.017885
    consa LILW        c 0.1
#
*
```

```
Gas_PP o
    minp        g-P 1.
    moutp        e-S c 0.52
    plf        c 0.85
    pll        c 30
    inv        ts 522 460 460 420 420 394 394 377 377
    fom        ts 8 7 7 6 6 6 6 6 6
    hisc        13764.        hc 1993 1061 1994 1061 1995 1061
     ↪  1996 1061 1997 1061 1998 1061 1999 1061 2000 1061 2001
     ↪  1061 2002 1061 2003 1771 2004 1126 2005 977 2006 461 2007
     ↪  229 2008 389 2009 1391 2010 1750 2011 999 2012 895 2013
     ↪  3610 2014 1550
    cmix        2 600
    ctime        c 2
    con1a FLEX        c 1
    con1a CO2        c 3.04
    con1a NOx        c 0.017
#
2. activity p
    minp        g-P 1.
    moutp        e-S c 0.34
    hisc        1570.
    outp t-F        c 0.51
    con1a FLEX        c 0.5
    con1a CO2        c 3.04
    con1a NOx        c 0.017
*
Oil_PP a
    minp        o-P 1.
    moutp        e-S c 0.34
    plf        c 0.85
    pll        c 30
    inv        c 600
    fom        c 46
    hisc        245.        hc 1993 84 1994 84 1995 84 1996 84
     ↪  1997 84 1998 84 1999 84 2000 84 2001 84 2002 84 2003 88
     ↪  2005 7 2007 30 2008 15 2009 39 2010 10 2011 32
```

```
    cmix        2 100
    ctime        c 2
    con1a FLEX        c 1
    con1a SO2        c 0.043
    con1a NOx        c 0.021
    con1a CO2        c 5.91
#
*
Coal_Dom_PP a
    minp        c-P 1.
    moutp        e-S c 0.4
    plf        c 0.85
    pll        c 40
    inv        ts 1279 1060 1060 925 925 843 843 792 792
    fom        ts 51 42 42 37 37 34 34 32 32
    hisc        4180.        hc 1993 627 1994 627 1995 627 1996
     ↪  627 1997 627 1998 627 1999 627 2000 627 2001 627 2002 627
     ↪  2003 20 2004 50 2005 680 2006 1080 2007 16 2009 135 2010
     ↪  30 2012 41 2013 37 2014 57
    cmix        2 160
    ctime        c 4
    con1a FLEX        c 0.15
    con1a SO2        c 0.035
    con1a NOx        c 0.035
    con1a CO2        c 3.19
#
2. activity v
    minp        c-P 1.
    moutp        e-S c 0.4
    vom        c 3.07
    con1a FLEX        c 0.15
    con1a SO2        c 0.0035
    con1a NOx        c 0.0175
    con1a CO2        c 3.19
*
Coal_Imp_PP c
    minp        l-P 1.
```

```
    moutp        e-S c 0.47
    plf        c 0.85
    pll        c 40
    inv        ts 2213 1783 1783 1518 1518 1356 1356 1255 1255
    fom        ts 89 71 71 61 61 54 54 50 50
    hisc        4417.        hc 2002 1012 2003 1320 2004 45 2005
     ↪ 141 2009 270 2010 1360 2011 625 2012 75 2014 1550
    cmix        2 320
    ctime        c 4
    con1a FLEX        c 0.15
    con1a SO2        c 0.035
    con1a NOx        c 0.035
    con1a CO2        c 3.07
#
2. activity b
    minp        l-P 1.
    moutp        e-S c 0.47
    vom        c 6.93
    con1a FLEX        c 0.15
    con1a SO2        c 0.0035
    con1a NOx        c 0.0175
    con1a CO2        c 3.07
*
Hydro_PP_Res p
    moutp        e-S c 1
    plf        c 0.3
    pll        c 60
    inv        c 3175
    fom        c 70
    hisc        3283.        hc 1979 500 1982 69 1984 138 1987
     ↪ 2503 1988 138 1989 54 1990 152 1991 340 1992 2529 1993 46
     ↪ 1994 159 1996 62 1997 169 1998 95 1999 359 2000 142 2001
     ↪ 38 2002 897 2003 337 2004 63 2005 261 2006 157 2007 332
     ↪ 2008 425 2009 636 2010 1251 2011 1252 2012 2417 2013 2298
     ↪ 2014 1084
    cmix        2 100
    ctime        c 4
```

```
    con1a FLEX        c 0.5
    con1a CO2        c 0.420
    consa 2sto        c -1
#
*
Hydro_PP_ROR s
    moutp        e-S c 1
    plf        c 0.3
    pll        c 60
    inv        c 2175
    fom        c 70
    hisc        1357.        hc 1986 7 1992 8 2003 23 2004 4 2005 593 2006 593 2007 593 2008 600 2009 682 2010 642 2011 646 2012 711 2013 908 2014 719
    cmix        2 20
    ctime        c 2
    con1a CO2        c 0.157
    con2a 1riv        c 1
    consa 1sto        c -1
    abda up        c 6800
#
*
Wind_PP z
    minp        w-P 1.
    moutp        e-S c 1
    plf        c 0.3
    pll        c 25
    inv        ts 1523 1323 1323 1196 1196 1114 1114 1062 1062
    fom        ts 35 30 30 27 27 25 25 24 24
    hisc        975.        hc 2002 136 2005 1 2006 39 2007 76 2008 217 2009 439 2010 529 2011 409 2012 532 2013 498 2014 755
    ctime        c 3
    con1a FLEX        c -0.08
    con1a CO2        c 0.07
#
*
```

```
Solar_PP x
    minp        s-P 1.
    moutp        e-S c 1
    plf        c 0.3
    pll        c 25
    inv        ts 3264 2851 2851 2585 2585 2415 2415 2305 2305
    fom        ts 21 18 18 16 16 15 15 15 15
    hisc        2.        hc 2014 40
    ctime        c 1
    con1a FLEX        c -0.05
    con1a CO2        c 0.14
#
*
Geo_PP c
    minp        e-P 1.
    moutp        e-S c 0.35
    plf        c 0.3
    pll        c 40
    inv        ts 3411 3334 3334 3276 3276 3231 3231 3196 3196
    fom        ts 178 174 174 171 171 168 168 166 166
    hisc        270.        hc 2002 15 2006 8 2008 7 2009 47 2010
     ↪  17 2011 20 2012 48 2013 149 2014 94
    cmix        2 1
    ctime        c 4
    con1a CO2        c 0.876
#
*
Bio_PP n
    minp        b-P 1.
    moutp        e-S c 0.35
    plf        c 0.3
    pll        c 40
    inv        ts 1491 1361 1361 1273 1273 1214 1214 1175 1175
    fom        ts 60 54 54 51 51 49 49 47 47
    hisc        164.        hc 2002 100 2006 6 2007 1 2008 17
     ↪  2009 22 2010 17 2011 19 2012 37 2013 37 2014 44
    cmix        2 3
```

```
    ctime        c 3
    con1a FLEX        c 0.3
    con1a CO2        c 0.219
#
*
Gas_Imp a
    moutp        g-P c 1.0
    pll        c 50
    inv        c 846
    fom        c 17
    vom        c 157.68
    hisc        53407.        hc 1988 5192 1995 1534 1996 11328
     ↪  1997 18880 1998 4720 2001 7788 2011 7080
    ctime        c 3
    mpa up        c 0 c 1.03
#
*
Oil_Imp a
    moutp        o-P c 1.0
    vom        c 173.45
    hisc        39107.
    mpa up        c 0 c 1.03
#
*
Oil_Ref a
    minp        o-P 1.
    moutp        o-D c 1
    pll        c 60
    inv        c 59.8
    fom        c 81
```

```
    hisc        36708.        hc 1961 1766 1962 339 1963 339 1964 339 1965 339 1966 339 1967 339 1968 339 1969 339 1970 339 1971 339 1972 4322 1973 493 1974 493 1975 493 1976 493 1977 493 1978 493 1979 493 1980 493 1981 493 1982 493 1983 493 1984 493 1985 493 1986 7131 1987 493 1988 493 1989 493 1990 493 1991 493 1992 493 1993 493 1994 493 1995 493 1996 493 1997 493 1998 493 1999 493 2000 493 2001 493 2002 493 2003 493 2004 493 2005 493 2006 493 2007 493 2008 493 2009 493 2010 493 2011 493 2012 493 2013 493 2014 493
    ctime        c 2
    outp b-F        c 0.142
    outp d-F        c 0.294
    outp g-F        c 0.174
    outp p-F        c 0.048
    outp f-F        c 0.124
    outp j-F        c 0.171
    outp l-F        c 0.047
    con1a CO2        c 2.31
#
*
Coal_Imp a
    moutp        l-P c 1
    vom        c 94.61
    hisc        26412.
    mpa up        c 0 c 1.03
#
*
Coal_Dom_F a
    minp        c-P 1.
    moutp        c-F c 1
    hisc        13591.
    con1a CO2        c 3.19
#
*
Coke_Prod a
    minp        c-P 1.
```

```
    moutp        o-F c 0.7
    hisc        3886.
    outp t-F        c 0.3
#
*
LWR_dummy a
    minp        l-D 1.
    moutp        k-D c 1.0
    consa q        c 1
#
*
LWR_fuel_prod a
    minp        u-N 1.
    moutp        w-N c 1.0
    vom        c 275
#
*
Enrichment a
    minp        r-N 1.
    moutp        u-N c 0.10758
    vom        c 8
    inp s-N        c 0.753
    consa depl        c 0.892
#
*
SWU a
    moutp        s-N c 1.0
    vom        c 110
#
*
Uranium_imp a
    moutp        r-N c 1.0
    vom        c 150
#
*
Spent_fuel_Trans a
    moutp        k-D c 1
```

```
    consa q         c -1
    consa L_in         c 1
#
*
Coal_Dom_Ext a
    minp         c-R 1.
    moutp         c-P c 1
    vom         c 94.61
    hisc         1486.9400000000001
    mpa up         c 0 c 1.03
#
*
Lignite_Ext a
    minp         l-R 1.
    moutp         c-P c 1
    vom         c 94.61
    hisc         20270.529999999999
    mpa up         c 0 c 1.03
#
*
Petrocoke_Imp h
    moutp         p-F c 1
    vom         c 346.9
    hisc         4123.
    con1a CO2         c 2.98
#
*
Solar_heat a
    minp         s-P 1.
    moutp         s-F c 1
    hisc         1067.
#
*
Bio_TD a
    minp         b-P 1.
    moutp         i-F c 1
    con1a CO2         c 3.15
```

```
#
*
Feedstock_Imp a
    moutp        b-F c 1
    vom        c 346.9
    hisc        316.
#
*
Biodiesel s
    minp        b-P 1.
    moutp        d-F c 0.49
    pll        c 60
    inv        ts 2025 2025 2025 1846 1846 1725 1725 1642 1642
    fom        ts 81 81 81 74 74 69 69 66 66
    hisc        102.        hc 2012 31 2013 42 2014 30
    ctime        c 2
    con1a CO2        c 1.72
#
*
Biomass a
    moutp        b-P c 1
    vom        c 47.30
    hisc        1881.
    abda up        c 13433
#
*
Solar a
    moutp        s-P c 1
    hisc        1069.
    abda up        c 8208000
#
*
Geothermal a
    moutp        e-P c 1
    hisc        4686.
    abda up        c 31500
#
```

```
*
Geo_heat a
    minp         e-P 1.
    moutp         s-F c 1
    hisc         1983.
    con1a CO2         c 0.876
#
*
Wind a
    moutp         w-P c 1
    hisc         975.
    abda up         c 48000
#
*
LPG_Imp a
    moutp         l-F c 1
    vom         c 346.9
    con1a CO2         c 1.99
#
*
Kerosene_Imp a
    moutp         j-F c 1
    vom         c 346.9
    con1a CO2         c 2.25
#
*
Gasoline_Imp a
    moutp         g-F c 1
    vom         c 346.9
    con1a CO2         c 2.19
#
*
Diesel_Imp a
    moutp         d-F c 1
    vom         c 346.9
    con1a CO2         c 2.34
#
```

```
*
Fuel_Oil_Imp a
    moutp        f-F c 1
    vom        c 346.9
    con1a CO2        c 2.44
#
*
Elec_Imp a
    moutp        e-S c 1
    vom        c 2000
#
*
resources:
fuel l-R
# Lignite/RESOURCES
    grade a
        volume        2465753.
*
fuel c-R
# Coal_Dom/RESOURCES
    grade a
        volume        440925.
*
endata
```

APPENDIX B

ENERGY LOAD REGIONS

```
loadregions:
ltype        seasonal
year        2015 January February March April May June July
  ↪ August September October November December
range         2015-01-01 2015-02-01 2015-03-01 2015-04-01
  ↪ 2015-05-01 2015-06-01 2015-07-01 2015-08-01 2015-09-01
  ↪ 2015-10-01 2015-11-01 2015-12-01 2016-01-01
season        January Workday SSH
day          Workday 22
name          aaa aab aac
length          0.25 0.5 0.25
day          SSH 9
name          aba abb
length          0.5 0.5
season        February Workday SSH
day          Workday 20
name          baa bab bac
length          0.25 0.5 0.25
day          SSH 8
name          bba bbb
length          0.5 0.5
season        March Workday SSH
day          Workday 22
name          caa cab cac
length          0.25 0.5 0.25
day          SSH 9
name          cba cbb
```

```
length        0.5 0.5
season        April Workday SSH
day          Workday 22
name          daa dab dac
length        0.25 0.5 0.25
day          SSH 8
name          dba dbb
length        0.5 0.5
season        May Workday SSH
day          Workday 21
name          eaa eab eac
length        0.25 0.5 0.25
day          SSH 10
name          eba ebb
length        0.5 0.5
season        June Workday SSH
day          Workday 22
name          faa fab fac
length        0.25 0.5 0.25
day          SSH 8
name          fba fbb
length        0.5 0.5
season        July Workday SSH
day          Workday 23
name          gaa gab gac
length        0.25 0.5 0.25
day          SSH 8
name          gba gbb
length        0.5 0.5
season        August Workday SSH
day          Workday 21
name          haa hab hac
length        0.25 0.5 0.25
day          SSH 10
name          hba hbb
length        0.5 0.5
season        September Workday SSH
```

```
day          Workday 22
name           iaa iab iac
length           0.25 0.5 0.25
day          SSH 8
name           iba ibb
length           0.5 0.5
season          October Workday SSH
day          Workday 22
name           jaa jab jac
length           0.25 0.5 0.25
day          SSH 9
name           jba jbb
length           0.5 0.5
season          November Workday SSH
day          Workday 21
name           kaa kab kac
length           0.25 0.5 0.25
day          SSH 9
name           kba kbb
length           0.5 0.5
season          December Workday SSH
day          Workday 23
name           laa lab lac
length           0.25 0.5 0.25
day          SSH 8
name           lba lbb
length           0.5 0.5
```

APPENDIX C

EXPERT ELICITATION SURVEY

Nuclear energy and climate change

The objective of this survey is to receive expert opinion for the study conducted by the Middle East Technical University (METU) under the Coordinated Research Project (CRP) of International Atomic Energy Agency titled "Assessments of the potential role of nuclear energy for climate change mitigation strategies". The questions are grouped under three sections: "Global development pathways", "Energy and climate change mitigation strategies" and "Energy and environmental behaviour". Finally there are questions related to the demographics of the sample group. Answering all the questions and reading the additional explanations would take approximately 30 minutes.

Your participation is on a voluntary basis and the necessary permission has been received from METU Applied Ethics Research Center. Answers will be kept confidential and only will be used by the researchers. The information will be elaborated together and used in scientific publications. The information provided will not be matched with your identity information. In case you feel uncomfortable you can stop the survey at any time. At the end of the survey, there is a link to the web page of the CRP where you can get more information on the study.

There are 14 questions in this survey

Global development pathways

1 [1]Thinking about the causes of climate change, which, if any, of the following describes your opinion?

Please choose **only one** of the following:

- ○ There is no such thing as climate change
- ○ Climate change is not happening now, we are experiencing climate variability
- ○ Climate change is happening now, and is entirely related to natural processes
- ○ Climate change is happening now, and is neither related to natural processes or human activities
- ○ Climate change is happening now, and is entirely related to human activities

2 [2]

Which of these two issues, if at all, do you think is more important?

- **Climate change - reducing the carbon emissions from human activities to prevent irreversible damage to the environment.**
- **Energy security - ensuring the supply and access of uninterrupted, secure and affordable energy for all.**

Please choose **only one** of the following:

- ○ Energy security is the only important issue
- ○ Both - but energy security has higher priority
- ○ Both are equally important
- ○ Both - but climate change has higher priority
- ○ Climate change is the only important issue

3 [3]

How important, if at all, do you perceive the following for responding to global climate change and sustainable development?

Please choose the appropriate response for each item:

	Not relevant/applicable	Not at all important	Slightly important	Moderately important	Very important	Extremely important
Investment for public education and health	○	○	○	○	○	○
Empowerment of national and international institutions	○	○	○	○	○	○
Reduction of inequalities between and within countries	○	○	○	○	○	○
Investment for technological development and innovation	○	○	○	○	○	○
Prevention of international and regional conflicts	○	○	○	○	○	○
Reduction of material and resource consumption	○	○	○	○	○	○
Respect for the natural environment and other species	○	○	○	○	○	○

4 [4]Thinking about nuclear energy as an option for climate change mitigation, which, if any, of the following describes your opinion?

Please choose **only one** of the following:

- ○ We should not use nuclear energy as the risks far outweigh those of climate change
- ○ We should explore all other energy options to reduce our carbon emissions before building a new nuclear power plant
- ○ Nuclear power plants should be built irrespective of any other energy options
- ○ I am willing to support nuclear energy if it would be helpful to support climate change mitigation
- ○ We need nuclear energy because we are not able to reduce our carbon emissions by using all other energy options

Energy and climate change mitigation strategies

5 [1]

How important, if at all, are the following for responding to climate change?

Please choose the appropriate response for each item:

	Not relevant/applicable	Not important	Slightly important	Moderately important	Important	Very important
Strengthening of cultural identity	○	○	○	○	○	○
Strengthening environmental rule-of-law	○	○	○	○	○	○
Empowerment of social charities and relief agencies	○	○	○	○	○	○
Investment for nature based services	○	○	○	○	○	○
Empowerment of businesses and citizens for nature management	○	○	○	○	○	○

6 [2]

How important, if at all, do you perceive the following energy sources for safe and reliable electricity generation?

Please choose the appropriate response for each item:

	Not important	Slightly important	Moderately important	Important	Very important
Bio-energy	○	○	○	○	○
Domestic coal	○	○	○	○	○
Imported coal	○	○	○	○	○
Natural gas	○	○	○	○	○
Geothermal power	○	○	○	○	○
Hydro-power	○	○	○	○	○
Wind energy	○	○	○	○	○
Solar energy	○	○	○	○	○
Fuel-oil	○	○	○	○	○
Nuclear energy	○	○	○	○	○

7 [3]

How safe, if at all, would you feel if any of the following installations were built near where you live?

Please choose the appropriate response for each item:

	Not at all safe	Slightly safe	Moderately safe	Very safe	Extremely safe
Coal power plant	○	○	○	○	○
Natural gas power plant	○	○	○	○	○
Biomass power plant	○	○	○	○	○
Wind or solar power plant	○	○	○	○	○
Hydro power plant	○	○	○	○	○
Nuclear power plant	○	○	○	○	○
Nuclear fuel cycle facility	○	○	○	○	○
Oil refinery	○	○	○	○	○
Natural gas processing and storage facility	○	○	○	○	○
Solid waste landfill	○	○	○	○	○
Radioactive waste processing and storage facility	○	○	○	○	○

Energy and environmental behavior

8 [1]Which transport mode do you mainly use for coming to and from your workplace?

Please choose **only one** of the following:

- Private car
- Commercial vehicle
- Personnel/public bus
- Metro/train
- Pedestrian/bicycle

9 [2]How often, if at all, do you apply the following for household energy efficiency and conservation?

Please choose the appropriate response for each item:

	Never	Rarely	Sometimes	Most of the time	Always
Optimize the flow and temperature of water during daily activities					
Turn off lights and other appliances when leaving the room					
Make sure the dish washer/washing machine is full before using it					
Decide what you want to do before opening the refrigerator door					
Store disposable materials in seperate trash bins					
Repair and reuse materials first instead of replacing them					
Keep windows and doors closed when heating/cooling the house					

10 [3]

How much, if at all, are you satisfied of the following for making things better by getting involved in responding to climate change and promoting sustainable development?

Please choose the appropriate response for each item:

	Very dissatisfied	Dissatisfied	Neutral	Satisfied	Very satisfied
National government	○	○	○	○	○
Local authorities	○	○	○	○	○
Scientists working for universities	○	○	○	○	○
Scientists working for government	○	○	○	○	○
Experts working for government	○	○	○	○	○
Non-governmental organizations	○	○	○	○	○
Community leaders	○	○	○	○	○
Private companies	○	○	○	○	○

Demographics

11 [1]

What is your gender?

Please choose **only one** of the following:

- Female
- Male

12 [3]

What is your age?

Please choose **only one** of the following:

- 18-24 years old
- 25-34 years old
- 35-44 years old
- 45 years or older

13 [2]

What is your professional background?

Please choose **only one** of the following:

- Engineering
- Law
- Social sciences
- Statistical sciences
- Other (specify)

Make a comment on your choice here:

14 [4]

What is the highest degree in school you have completed?

Please choose **only one** of the following:

- Bachelor's degree
- Master's degree
- Doctorate degree
- Other (specify)

Make a comment on your choice here:

Thank you for participating in our survey. If you want to receive further information you can contact Chief Scientific Investigator of the Coordinated Research Project Prof. Dr. Ramazan Sari (rsari@metu.edu.tr) by e-mail.

Please submit by 31.07.2019 – 00:00

Submit your survey.
Thank you for completing this survey.

APPENDIX D

R CODE FOR MCA OF MODELING RESULTS

```
library(MCDA)

# load csv file

pT <- read.csv(file = "ssp3_mcda.csv", header=TRUE, row.names=1)

# the criteries for MCA variables

criteriaMinMax <- c("min","max","min","min")

names(criteriaMinMax) <- colnames(pT)

plotRadarPerformanceTable(pT[1:4], criteriaMinMax, overlay=FALSE,
 ↪  bw=TRUE, lwd =5)

##################################
# second attempt                 #
# normalization and weighted sum #
##################################

# 5 barplots
par(mfrow=c(2,2))
for (i in 1:dim(pT)[2]){
  yaxis <- range(pT[,i])*c(0.90,1.1)
  if (criteriaMinMax[i] =="min")
    oPT <- pT[order(pT[,i],decreasing=FALSE),]
  else
```

```
    oPT <- pT[order(pT[,i],decreasing=TRUE),]
  name <-paste(colnames(pT)[i]," (",criteriaMinMax[i],")", sep="")
  barplot(oPT[,i], main=name, names.arg = rownames(oPT), density = i*10, ylim = yaxis, xpd=FALSE, cex.names = 0.8)
}

# normalization of the data from the performance table

normalizationTypes <- c("percentageOfMax","percentageOfMax","percentageOfMax","percentageOfMax")

names(normalizationTypes) <- c("g1","g2","g3","g4")

nPT <- normalizePerformanceTable(pT,normalizationTypes)

# weights from expert elicitation survey using 5-point Likert scale

w <- c(-5,3,-4,-3)
names(w) <- colnames(pT)
ws<-weightedSum(nPT,w)

# rank the scores of the alternatives
rank(-ws)
```