CRANFIELD UNIVERSITY

Oluwatosin Christiana Murele

Design and Planning of Energy Supply Chain Networks

School of Water, Energy and Environment
PhD, Full-Time

PhD
Academic Years: 2016 - 2019

Principal supervisor: Dr. Dawid P. Hanak
Associate supervisor: Prof. Phil Hart

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ABSTRACT

During a period of transformation towards decarbonised energy networks, maintenance of a reliable and secure energy supply whilst increasing efficiency and reducing cost will be key aims for all energy supply chain (ESC) networks. With the knowledge that about 80% of global energy is obtained from fossil fuels, appropriate design and planning of its supply chain networks is inevitable. Notwithstanding, renewable energy sources, such as biomass, solar, wind and geothermal, will also play important roles in the future ESCs as climate change mitigation becomes an increasingly important concern. To achieve this aim, energy systems optimization models were derived; (i) for the simultaneous planning of energy production and maintenance in combined heat and power (CHP) plants for overall cost reduction, with results obtained benchmarked against data from industry; (ii) for biomass integration into ESC networks for emissions reduction and benchmarking it against data from literature and the governing equations solved for optimality using the General Algebraic Modelling System (GAMS) software. Further, energy survey questionnaires were developed using the Qualtrics online survey tool and same disseminated to individuals in some counties of the United Kingdom (UK) with the aim of proposing strategies for improved renewable energy (RE) embracement in the UK energy mix. The case study of the coal-fired CHP plant predicted a 21% reduction in annual total cost in comparison to the implemented industrial solution that follows a predefined maintenance policy, thereby, enhancing the resource and energy efficiency of the plant. Additionally, the optimization model for integrating biomass into energy supply chain networks indicated that a reduction in the emissions level of up to 4.32% is achievable on integration of 5-8% of biomass in the ESC with a 4.57% increase in the total cost of the ESC network predicted at biomass fraction of 7.9% in the mixed fuel, indicating that the cost increment in a biomass and coal co-fired plant can be offset with the introduction of effective carbon pricing legislation.

Keywords: Energy networks, renewable energy sources, energy systems optimization, combined heat and power (CHP) plants, optimization model.

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TABLE OF CONTENTS

ABSTRACT i
ACKNOWLEDGEMENTS iii
LIST OF FIGURES ix
LIST OF TABLES xii
LIST OF ABBREVIATIONS xiv
LIST OF NOMENCLATURES (MODEL FOR KUS CHP PLANT) xv
LIST OF NOMENCLATURES (MODEL FOR BIOMASS CO-FIRING WITH COAL) xviii
1 INTRODUCTION 1
  1.1 Background 1
  1.2 Motivation 7
  1.3 Aim and objectives of the research project 13
  1.4 Novelty and correlation of project outputs 13
  1.5 Outline of PhD thesis 16
  1.6 Dissemination from the PhD thesis 18
    1.6.1 Journal and conference publications 18
    1.6.2 Conference and workshop presentations 19
2 LITERATURE REVIEW 20
  2.1 Energy generation, demand and policies 20
    2.1.1 Global energy mix 20
    2.1.2 The EU energy roadmap 23
    2.1.3 The Montreal protocol 25
    2.1.4 The Kyoto protocol 25
    2.1.5 The Climate Change Act 2008 26
    2.1.6 Paris agreement 26
    2.1.7 Comparisons between 2020, 2030 and 2050 renewable energy policies 27
    2.1.8 Emissions trading scheme & policy on EU/UK energy targets 28
    2.1.9 Evolvement of renewable energy in the UK 29
    2.1.10 Issues surrounding lower levels of renewable energy share in the current global energy mix 29
  2.2 Biomass classifications (based on sources) 30
    2.2.1 Sources of biomass in diverse/selected regions 31
    2.2.2 Comparison of biomass and coal fuel characteristics 32
  2.3 Energy production from solid fuels 33
    2.3.1 Coal-fired power plant 33
    2.3.2 Co-firing of coal and biomass 34
  2.4 Energy supply chain networks 42
    2.4.1 The energy supply chain networks 42
    2.4.2 Fossil fuel-based energy supply chain networks 46

2.4.3 Biomass supply chain networks 47
2.4.4 Potential and existent locations for biorefineries/bioenergy plants ... 58
2.4.5 Some challenges encountered in the biomass supply chain networks 61
2.5 Modelling and optimisation of energy supply chains 62
2.5.1 Mathematical frameworks for supply chain systems 62
2.5.2 Mathematical modelling techniques for biomass supply chain design and analysis 63
2.5.3 Models overview for operation and maintenance planning of energy systems 64
2.5.4 Various optimisation-based approaches for the design and planning of energy supply chain networks 66
2.5.5 Optimization models for the design and planning of energy supply chain networks 66
2.6 Research methods 71
2.7 Sampling methods 73
3 METHODOLOGY 77
3.1 Description on theory and methods of the Karaganda Utility System 77
3.2 Proposed optimization framework for Karaganda Utility System 78
3.2.1 Optimization Framework for case study of Karaganda Utility System 82
3.2.2 Generation level bounds for boiler and turbine units and heat balance in the steam pipeline 82
3.2.3 Extreme operating regions for turbine units..................................... 83
3.2.4 Electricity and heat balance in turbine and boiler units (energy demand) 84
3.2.5 Startup and shutdown action for boiler and turbine units.................. 85
3.2.6 Minimum run and idle times for boiler and turbine units 85
3.2.7 Maximum runtimes for boiler and turbine units................................ 85
3.2.8 Maintenance for boiler and turbine units: flexible time-windows policy 86
3.2.9 Objective function.. 86
3.2.10 Case Study of Karaganda Utility System (KUS)............................. 87
3.3 Karaganda Utility System (KUS) results, analysis and discussion 93
4 DESCRIPTION ON THEORY AND METHODS OF BIOMASS CO-FIRING WITH COAL 103
4.1 Proposed state task network (STN) approach 103
4.2 Modelling Approach 105
4.3 Optimisation Framework 107
4.3.1 Constraints for the design: Technologies establishment and corresponding expansions for installed capacities 107
4.3.2 Overall capacity for technologies establishment and expansions .. 108

4.3.3 Availability for raw materials states 109
4.3.4 Connection and balance for applicable states 110
4.3.5 Objective function 111
4.4 Description of the case study 113
4.5 Results, analysis and discussion on integrating biomass into energy supply chain networks 117
5 METHODS FOR RESEARCH DATA COLLECTION 126
5.1 Methodology for energy survey and analysis using qualtrics 126
5.2 Energy survey research design 127
5.3 Energy survey with consideration given to the UK energy mix 128
5.4 Energy survey results, analysis and discussion 131
5.4.1 Section A: Background information of respondents and awareness level on renewable energy technologies 131
5.4.2 Section B: Impact of incentives on renewable energy technologies 136
5.4.3 Section C: Introduction of varying energy mix 138
5.4.4 Section D: Improvement in Government policy 139
5.4.5 Propositions for improved renewables embracement in the UK energy mix 142
6 GENERAL DISCUSSION 143
7 CONCLUSIONS 149
7.1 Efficient planning of energy production and maintenanceof large-scale combined heat and power plant 149
7.2 Integrating biomass into energy supply chain networks 149
7.3 Strategies for improved embracement of renewable energy in the UK energy mix 150
REFERENCES 153
APPENDICES 167
Appendix A GAMs equation codes for the case study of combined heat and power plants at Karaganda utility system (KUS) 167
A.1 Equation codes for optimized case (OPT-3) 167
A.2 Data for OPT-3 181
A.3 Equation codes for optimized cases (OPT-1 and OPT-2) 187
Appendix B 196
B.1 Gams illustration for the case study of co-firing biomass with coal using the state task network (STN) approach 196
B.2 Equation codes for co-firing biomass with coal 202
B.3 GAMS data codes for biomass co-firing with coal 207
B.4 GAMS illustration for coal-only fired plants 220
B.5 STN representation for biofuel supply chain 235
B.6 Illustration of gasification in biofuel supply chain using the STN approach 235

Appendix C Energy survey using qualtrics online survey tool 236
  C.1 Cures ethics approval for conducting surveys 236
  C.2 Energy survey research questionnaire 237
  C.3 Data tables for responses obtained in the energy survey conducted ... 242
Appendix D 247
  D.1 Turbines 1 to 6. Normalized operating load profiles for OPT-3 solutions 247
  D.2 Boilers 1 to 7. Normalized operating load profiles for OPT-3 solutions 249
  D.3 Parameter values for the case study of Karaganda utility systems 252
  D.4 Parameter values for the case study of integrating biomass into energy supply chain networks 255
Appendix E 258
  E.1 Cost comparison for KUS, OPT-1,OPT-2 and OPT-3 solution approaches 258

LIST OF FIGURES

Figure 1-1 Carbon Dioxide Emissions on a global basis (1850-2030) (IEA, 2016; Oak Ridge National Laboratory, 2017) 1

Figure 1-2 Share of a) global power generation and b) CO_2 intensity of global power producers (IEA, 2019b) 3

Figure 1-3 Sector categorization of gross global GHG emissions in MtCO2 equivalent (IEA, 2016) 4

Figure 1-4 Gas type categorization of gross global GHG emissions in 2013 (IEA, 2016) 5

Figure 1-5 Carbon accumulation on a global basis (NOAA, 2012) 7

Figure 1-6 Distribution of global electricity generation sources for the year 2017 (Petrova, 2018) 8

Figure 1-7: Energy-related CO_2 emissions (IEA, 2018b) 9

Figure 2-1 Global total primary energy supply fuel-wise (IEA, 2019f) 20

Figure 2-2 World primary energy consumption fuel-wise (2014) (IEA, 2017). .. 21

Figure 2-3 Share of renewable energy in total generation considering electricity sector scenarios (Climate Action Tracker, 2018) 24

Figure 2-4 Potential emissions reductions in the electricity sector by year 2050 (Climate Action Tracker, 2018) 24

Figure 2-5 Emission gaps for the year 2030 (Climate Action Tracker, 2019) ... 27

Figure 2-6 Emissions Trading Scheme (Energyryod, 2013) 29

Figure 2-7 Design of a coal-fired power plant and conversion of coal into electricity (World Coal Association, 2019) 34

Figure 2-8 Coal-fired power plants (Strother, 2015) 34

Figure 2-9 Co-firing of coal with biomass and waste in full-scale suspension-fired boilers (Johansen et al., 2012) 36

Figure 2-10 Direct addition of woodchips on a coal conveyor at Wallerawang Power Station, Australia (Koppejan and Baxter, 2013) 37

Figure 2-11 Energy supply chain network (QCA, 2019) 44

Figure 2-12 Natural gas-fired power plant (PowerGrid International, 2016) 47

Figure 2-13 Biomass Supply Chain representation (Toka et al., 2010) 50

Figure 2-14 Generic biomass supply chain design (Rentizelas et al., 2009b) .. 51

Figure 2-15 Factors considered for model development in a Biomass Supply Chain (Sharma et al., 2013) 58

Figure 2-16 The Ironbridge power plant at Severn Gorge, UK (Power stations of the UK, 2019) 60

Figure 2-17 Drax biomass storage domes (Drax Power Station, 2017) 61

Figure 2-18 Types of research methods 72

Figure 2-19: Categorization of sampling methods (HealthKnowledge, 2009) ... 75

Figure 3-1 KUS CHP plant layout (red boxes: boilers, blue circles: turbines, RCU: reduction cooling unit) 80

Figure 3-2 Operating regions for turbine units. 84

Figure 3-3 Annual profiles for electricity demand and heat demand per heat network (MW). 92

Figure 3-4 Maintenance plans for boilers for all solution approaches. 94

Figure 3-5 Maintenance plans for turbines for all solution approaches. 94

Figure 3-6 Comparison of annual total cost breakdown between KUS and OPT-3 (%) 95

Figure 3-7 Cost terms for OPT-3 compared to those of KUS solution 96

Figure 3-8 Aggregated total cost profiles for KUS solution and optimized solutions OPT-2 and OPT-3. 96

Figure 3-9a Turbines 1 to 3. Normalized operating load profile for KUS solution (figures on the left), and operating load deviation profile for OPT-3 from KUS solution (figures on the right). 98

Figure 3-10a Boilers 1 to 3. Normalized operating load profile for KUS solution (figures on the left), and operating load deviation profile for OPT-3 from KUS solution (figures on the right). 100

Figure 4-1 General representation of state-task network (STN) 105

Figure 4-2 Major constraints for the proposed approach 106

Figure 4-3: Illustrative energy state-task network for energy supply chain network 115

Figure 4-4 Normalized demand profile graph for energy resource produced in both internal regions (*r2.s3, r2.s6, r2.s7*) and external region (*r3.s7*) 118

Figure 4-5 Cumulative demand graph for states (*s*) in regions (*r)* obtained by dividing the individual demand at every time period by the maximum value at each state and region. 119

Figure 4-6 Inventory profile graph for energy material resource states *(s)* that can be stored in regions (*r)* where applicable. 119

Figure 4-7 Effect of biomass fraction in the mixed solid fuel on the total cost of energy supply chain network 120

Figure 4-8: Overall capacity expansion planning per associated technologies (*q*) in regions (*r*) and at time periods (*t*) 123

Figure 4-9a Total cost breakdown for ESC network with biomass integration 124

Figure 5-1Share of survey respondents from target counties in the UK 130

Figure 5-2 Age of survey respondents from target counties in the UK 132

Figure 5-3 Respondents’ degree/level of qualification 132

Figure 5-4 Respondents profession/industry category 134

Figure 5-5 Medium of awareness of renewable energy 136

Figure 5-6 Level of effectiveness of internet and social media 136

Figure 5-7 Incentives on renewable energy generation 138

Figure 5-8 Renewable energy area for exploration 139

Figure 5-9 Type of energy in use by respondents 140

Figure 5-10 Shift from conventional sources of energy generation and usage141

LIST OF TABLES

Table 2-1 2020, 2030 and 2050 climate and energy framework targets at a glance (European Commission, 2007, 2014, 2018) 28

Table 2-2 Higher Heating Values (HHV) for coal and biomass (Iowa State University, 2011)... 32

Table 2-3 Comparison of biomass characteristics with coal (similarities and differences) (Pace University, 2000)... 38

Table 2-4 Table showing differences in chemical composition of Pennsylvanian's biomass and coal (Bain et al., 2003; Miller and Tillman, 2008).................. 39

Table 2-5 Biomass conversion processes 54

Table 2-6 A presentation of some of the world's largest biomass power plants that are in operation (MW) 59

Table 3-1 Operating levels bounds for desired and extreme operating regions and maximum outlet heat flows for turbines 89

Table 3-2 Maintenance data (including starting times for actual KUS solution) 91

Table 4-1 Storage technologies available per state and region...................... 116

Table 4-2: Minimum ($\boldsymbol{\gamma}$min) and maximum ($\boldsymbol{\gamma}$max) capacity expansion level of associated technology, fixed operating cost for total installed technology ($\boldsymbol{\delta}$), costs associated with states production through conversion technologies ($\boldsymbol{\pi}$), Zulkafli and Kopanos, (2018a), investment cost for technology establishment ($\boldsymbol{\varepsilon}^0$) and cost required to increase the capacity of a technology ($\boldsymbol{\varepsilon}$) 116

Table 6-1: Applicability and limitations of the developed optimization models 144

Table C-1 Respondents' age... 242

Table C-2 showing respondents' profession/industry category 242

Table C-3 Degree/qualification of respondents 242

Table C-4 Energy type 242

Table C-5 Involvement in renewable energy generation 243

Table C-6 Renewable energy usage 243

Table C-7 Level of primary renewable energy activity.................................... 243

Table C-8 Frequency of renewable energy usage.. 244

Table C-9 Energy price 244

Table C-10 Renewable energy area for exploration....................................... 244

Table C-11 Reason for renewable energy exploration 244
Table C-12 Awareness level on renewable energy technologies (RETs)....... 245
Table C-13 Level of effectiveness of internet and social media...................... 245
Table C-14 Level of shift from conventional sources of energy generation 245
Table C-15 Likely impact of incentives on renewable energy generation....... 245
Table C-16 Satisfaction received from renewable energy usage 246

LIST OF ABBREVIATIONS

BSC	Biomass supply chain
BECCS	Bio-energy with carbon capture and storage
CHP	Combined heat and power
CPLEX	IBM ILOG CPLEX Optimisation Studio
DME	Dimethyl ether
EFB	Empty fruit bunch
ESC	Energy supply chain
ETBE	Ethyl tert-butyl ether
ETS	Emissions trading scheme
GAMS	General algebraic modelling system
GHG	Greenhouse gas
HFCs	Hydrofluorocarbons
HHV	Higher heating value
LLV	Lower heating value
LP	Linear programming
MILP	Mixed integer linear programming
NERT	National emissions reduction target
NPS	New policies scenario
OECD	Organisation for Economic Co-operation and Development
OPT-1	Optimized case 1
OPT-2	Optimized case 2
OPT-3	Optimized case 3
PFCs	Perfluorocarbons
POME	Palm oil mill effluent
RE	Renewable energy
SDG	Sustainable development goals
STN	State task network

LIST OF NOMENCLATURES (MODEL FOR KUS CHP PLANT)

Indexes / Sets

$i\epsilon I$	units (boilers and turbines)
$i\epsilon I^B$	set of boiler units (MW)
$i\epsilon I^T$	set of turbine units (MW)
$i\epsilon I_j^T$	set of turbine units $i\epsilon I^T$ that are connected to heat network j (MW)
$j\epsilon J$	heat networks (note: a reduction cooling unit is associated to each heat network)
$t, t'\epsilon T$	time periods (days)

Binary Variables

$F_{(i,t)}$	= 1, if unit i stops operating at the beginning of time period t, zero if otherwise
$S_{(i,t)}$	= 1, if unit i starts operating at the beginning of time period t, zero if otherwise
$W_{(i,t)}$	= 1, if the maintenance task of unit i starts at the beginning of time period t
$X_{(i,t)}$	= 1, if unit i operates during time period t
$Y_{(i,t)}$	= 1, if turbine unit $i\epsilon I^T$ operates during time period t within the desired operating region
$Y_{(i,t)}^+$	= 1, if turbine unit $i\epsilon I^T$ operates during time period t within the upper extreme operating region
$Y_{(i,t)}^-$	= 1, if turbine unit $i\epsilon I^T$ operates during time period t within the lower extreme operating region

Continuous Variables (non-negative)

E_t^{buy}	electricity purchases in time period t (or unsatisfied electricity demand) (\$/MWh)
E_t^{ex}	excessive electricity generation in time period t (MWh)
$E_{(i,t)}^T$	electricity generation level of turbine unit $i\epsilon I^T$ in time period t (MWh)
$H_{(j,t)}^{buy}$	heat purchases for heat network j in time period t (or unsatisfied heat demand) (MWh)
$H_{(j,t)}^{ex}$	excessive heat generation for heat network j in time period t (MWh)
$H_{(j,t)}^{RCU}$	direct heat flow to heat network j (via its associated reduction cooling unit) in time period t (MWh)

$Q^{B}_{(i,t)}$	heat generation level of boiler unit $i\epsilon I^{B}$ in time period t (MWh)
$Q^{Tin}_{(i,t)}$	inlet heat flow to turbine $i\epsilon I^{T}$ in time period t (MWh)
$Q^{Tout}_{(i,t)}$	outlet heat flow from turbine $i\epsilon I^{T}$ in time period t (MWh)

Parameters (Greek symbols)

$\alpha_{(i,t)}$	startup cost for unit i in time period t (\$)
β^{E}_{t}	factor for internal electricity requirements of the plant in time period t(%)
β^{H}_{t}	factor for internal heat requirements of the plant in time period t (%)
γ_{i}	number of time periods before the beginning of the current time horizon that unit i has been continuously operating since its last startup (days)
δ_{i}	maximum runtime for unit i (continuous operation from its startup) (days)
$\Delta\varepsilon^{+}_{(i,t)}$	maximum operating level for the upper extreme operating region of turbine unit $i\epsilon I^{T}$ in time period t (MW)
$\Delta\varepsilon^{-}_{(i,t)}$	minimum operating level for the lower extreme operating region of turbine unit $i\epsilon I^{T}$ in time period t (MW)
$\varepsilon^{max}_{(i,t)}$	maximum operating level for the desired operating region of turbine unit $i\epsilon I^{T}$ in time period t (MW)
$\varepsilon^{min}_{(i,t)}$	minimum operating level for the desired operating region of turbine unit $i\epsilon I^{T}$ in time period t (MW)
ζ^{el}_{t}	electricity demand in time period t (MWh)
$\zeta^{heat}_{(j,t)}$	heat demand for heat network j in time period t (MWh)
$\eta_{(i,t)}$	efficiency for turbine unit $i\epsilon I^{T}$ and boiler units $i\epsilon I^{B}$ in time period t (%)
η^{RCU}_{j}	heat efficiency factor for reduction cooling unit associated to heat network j (%)
$\theta^{max}_{(i,t)}$	maximum heat generation level for boiler unit $i\epsilon I^{B}$ in time period t (MW)
$\theta^{min}_{(i,t)}$	minimum heat generation level for boiler unit $i\epsilon I^{B}$ in time period t (MW)
$\theta^{Tmax}_{(i,t)}$	maximum outlet heat flow from turbine $i\epsilon I^{T}$ in time period t (MW)
$\kappa_{(i,t)}$	maintenance cost for unit i if maintenance starts in time period t (\$)
λ^{buy}_{t}	cost for acquiring electricity from externals sources in time period t (\$)
λ^{ex}_{t}	cost for excessive electricity generation in time period t (\$)
$\mu^{buy}_{(j,t)}$	cost for acquiring heat from externals sources for heat network j in time period t (\$)

$\mu_{(j,t)}^{ex}$	cost for excessive heat sent (i.e., disposed heat) to heat network j in time period t (\$)
M	a large number
ν_i	duration of maintenance task for unit i (days)
$\vartheta_{(r',r,s,p,q,t)}$	Transfer cost for states considered as useful products $s \in S^u$ to points of demand (money units)
$\xi_{(i,t)}$	fuel cost for boiler unit i in time period t (\$/ton)
$\pi_{(i,t)}$	fixed operating cost for unit i in time period t (\$)
$\rho_{(i,t)}^{+}$	penalty for turbine $i \epsilon I^T$ for operating in the upper extreme operating region
$\rho_{(i,t)}^{-}$	penalty for turbine $i \epsilon I^T$ for operating in the lower extreme operating region
τ_i^{max}	latest starting time for the maintenance task of unit i (i.e., upper bound of time-window) (days)
τ_i^{min}	earliest starting time for the maintenance task of unit i (i.e., lower bound of time-window) (days)
$\varphi_{(i,t)}$	shutdown cost for unit i in time period t (\$)
ψ_i	minimum idle time for unit i (from its last shutdown) (day)
ω_i	minimum runtime for unit i (from its last the startup) (days)
Cq_t	fuel calorific value in time period t (MWh)
$loss_i$	heat losses coefficient for boiler unit $i \epsilon I^B$ (%)

LIST OF NOMENCLATURES (MODEL FOR BIOMASS CO-FIRING WITH COAL)

Indexes / Sets

$p \in P$	tasks (biomass/coal exploitation, pre-processing, conversion, transfer)
$q \in Q$	technologies (biomass/coal exploitation, conversion, transfer, storage: intermediate site and infield storage at the power station
$r \in R$	regions (internal and external)
$s \in S$	states (raw materials, energy material resources, energy forms) (relative units, r.u)
$t, t' \epsilon T$	time periods (years)

Subsets

P^-_s	tasks that consume states (input state)
P_s^+	tasks that produce states (output state)
P_s^F	tasks involving raw material state
P_s^T	tasks that could transfer state *s*
Q^C	conversion technologies
Q^E	raw materials/biomass exploitation technology
Q^E_r	raw materials/biomass exploitation technologies in region *r*
Q^G	storage technologies (inclusive of intermediate, site and infield storage at power station)
$Q^G_{(s,r)}$	storage technologies for states in region *r*
Q^{PRC}_r	pre-processing, conversion, and biomass/coal exploitation technologies in region *r*
Q^{TR}	transfer technologies
$Q^{TR}_{(r, r')}$	technologies that can transfer states from region *r* to r'
Q_p	technologies that could perform tasks *p*
Q_r	technologies that could be installed in regions *r*
Q_s	technologies that involve states *s*

R^{ex}	external regions of the energy supply chain networks
R^{in}	internal regions of the energy supply chain networks
R_r^{TR}	regions that can transfer states between each other
S_r^{D}	states s that can be disposed in region *r*
S^{F}	fossil fuel raw material state (units)
S_r^{G}	states s that can be stored in region *r*
S^{rm}	States that are considered as raw materials
S^{rm}_renew	renewable raw material state (units)
S_r^{U}	states *s* that have demand in region *r* (represented as demand or useful product states) (units)
S_r	states that are present in region *r*

Binary Variables

$V_{(r,q,t)}$	=1, if biomass/coal exploitation, pre-processing and conversion technologies are established for the first time in region *r* at time period *t*, zero if otherwise.
$V^{G}_{(r,s,q,t)}$	=1, if storage technology *q* for state *s* is established for the first time in region *r* at time period *t*, zero if otherwise.
$Z_{(r,q,t)}$	=1, if capacity of biomass/coal exploitation, pre-processing and conversion technology q begins installing in region *r* at time period *t*, zero if otherwise.
$Z^{G}_{(r,s,q,t)}$	=1, if capacity of storage technology q for state *s* begins installing in region *r* in time period *t*, zero if otherwise.
$Z^{TR}_{(r,r',q,t)}$	=1, if capacity of transfer technology *q* starts installing in region *r* in time period *t,* zero if otherwise.

Continuous Variables (non-negative)

$C_{(r,q,t)}$	overall capacity of conversion or local exploitation technology *q* in region *r,* at time period *t*
$C^{G}_{(r,s,q,t)}$	overall capacity of storage technology *q* that can store states in region *r*, at time interval t

$C^{TR}{}_{(r,r',q,t)}$	overall capacity of transfer technology q that can that can transfer states from region *r* to region *r*' in time period *t*
CM_t	cost of raw materials at every time period *t (relative money units, rmu)*
$D_{(r,s,t)}$	quantity of disposable states (units)
DC_t	cost of disposing unwanted states to the environment (penalty) (rmu)
$E_{(r,q,t)}$	Capacity increase of conversion technology *q* in region r, at time interval t
$E^{G}{}_{(r,s,q,t)}$	capacity increase of storage technology that can store states in region *r*, at time interval t
$E^{TR}{}_{(r,r',q,t)}$	capacity increase of transfer technology *q* that can that can transfer states from region *r* to region *r'* in time period *t*.
FAC_t	fixed asset cost in time period *t (*relative money units, rmu)
FAC_t^{TR}	transfer network cost in time period *t* (rmu)
FOC_t	fixed operating cost in time period *t* (rmu)
$G_{(r,s,t)}$	stock of states that remain in region r at the end of time period *t* (units)
HC_t	cost of producing useful product states' at time period *t* (rmu)
IC_t	cost of inventory for states in time period *t* (rmu)
$M_{(r,r',q,t)}$	amount/quantity of states pre-processed, converted or transferred by task *p*, with the use of technology *q* from region *r* to *r*' in period *t (units)*
$N_{(r,s,t)}$	quantity of states with unmet demands (units)
NS_t	penalty (cost) for no-sales, i.e unmet demands (rmu)
TRC_t	transfer cost for useful product states within internal regions and that of sales to external regions (rmu)
VOC_t	variable operating cost in time period *t (rmu)*

Parameters (Greek symbols)

$\alpha_{(r,r,p,q,t)}$	bounds on the available capacities for both conversion and transfer tasks
$\beta_{(r,s,t)}$	bounds on inventory levels on states that can be stored $s \in S^G$ (units)
$\beta^0_{(r,s)}$	initial level of inventory for all states in all regions (units)
$\gamma_{(r,q,t)}$	bounds on allowable expansion levels for pre-processing, conversion and storage technologies
$\gamma^{TR}_{(r,r',t)}$	bounds on allowable expansion levels for transfer technologies $q \in Q^{TR}$
$\delta_{(r,q,t)}$	fixed operating cost for the total installed capacities of technology *q.(rmu)*
$\varepsilon^0_{(r,q,t)}$	initial investment cost required to establish a technology (money unit/unit)
$\varepsilon_{(r,q,t)}$	investment cost needed to expand the capacity of an already established technology (money unit/unit)
$\zeta_{(r,s,t)}$	demand for useful products states $s \in S^u$ in region r in time period *t (units)*
$\eta_{(r,s,t)}$	co-efficient of deterioration for states that can be stored $s \in S^G$ (%)
$\kappa_{(s,p,q)}$	co-efficient for input/output states for tasks that could be performed by technology q
$\lambda_{(r,s,t)}$	co-efficient of holding cost for storable states
$\lambda^D_{(r,s,t)}$	co-efficient of penalty for causing pollution through the disposal of unwanted substances into the environment.
$\mu_{(r,q,t)}$	time of installation for technology *q* in region *r* or the duration of constructing an additional facility, for an implementation start in period *t.(days)*
M	a large number
$\vartheta_{(r',r,s,p,q,t)}$	Transfer cost for states considered as useful products $s \in S^u$ to points of demand (money units)

$\pi_{(r,s,p,q,t)}$	cost of states production through conversion technology (mu)
$\varphi_{(r,q)}$	Initial installed capacity for biomass/coal exploitation, $q \in Q^{E}$, pre-processing and conversion technologies, $q \in Q^{PRC}$ in region *r* *(units)*
$\varphi^{G}_{(r,s,q)}$	Initial installed capacity for storage technology $q \in Q^{B}$ in region *r* *(units)*
$\varphi^{TR}_{(r,r',q)}$	Initial installed capacity for transfer technology $q \in Q^{TR}$ that connects two regions (units)
$\psi_{(r,s,p,q,t)}$	raw material cost money (units)
$\omega_{(r,s,t)}$	maximum available amount of raw material (units)

1 INTRODUCTION

1.1 Background

Global energy demand increased by 2.3% in the year 2018, denoting the quickest rise in the last decade which has been attributed to a strong global economy in addition to robust needs in the heating and cooling sectors of some regions around the world (International Energy Agency, 2019).

Since 1990, the strength of CO_2 emissions from electricity generation on a global level was steady, however, by early 2010s, emissions growth in global electricity generation was consistent with global electricity demand (Figure 1-1). Although, in the last few years, there has been a dissociation from the levels reported in the early 2010s, demand in electricity continues to rise, while rate of growth in emissions from power generation is on the decline (Pavarini and Mattion, 2019).

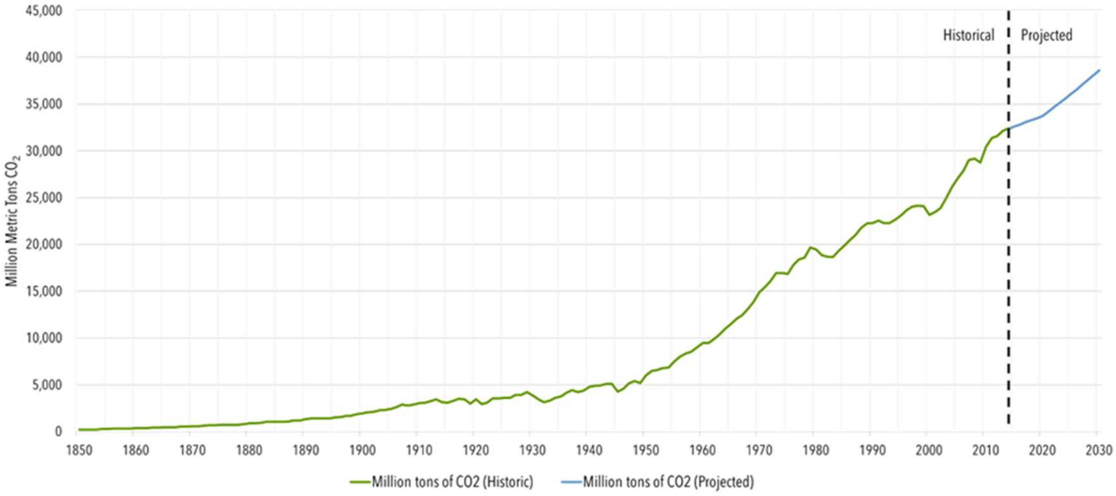


Figure 1-1 Carbon Dioxide Emissions on a global basis (1850-2030) (IEA, 2016; Oak Ridge National Laboratory, 2017)

At the moment, CO_2 emissions from power generation alone account for about 40% of emissions from energy related sources and over 25% of global greenhouse gas (GHG) emissions (Pavarini and Mattion, 2019). As reported by World Energy Organisation's net policies scenario commentaries, for about 27 years, increment in electricity generation more than doubled, reaching a value of about 26,000 TWh in the year 2017 and forecasted to reach a value of over

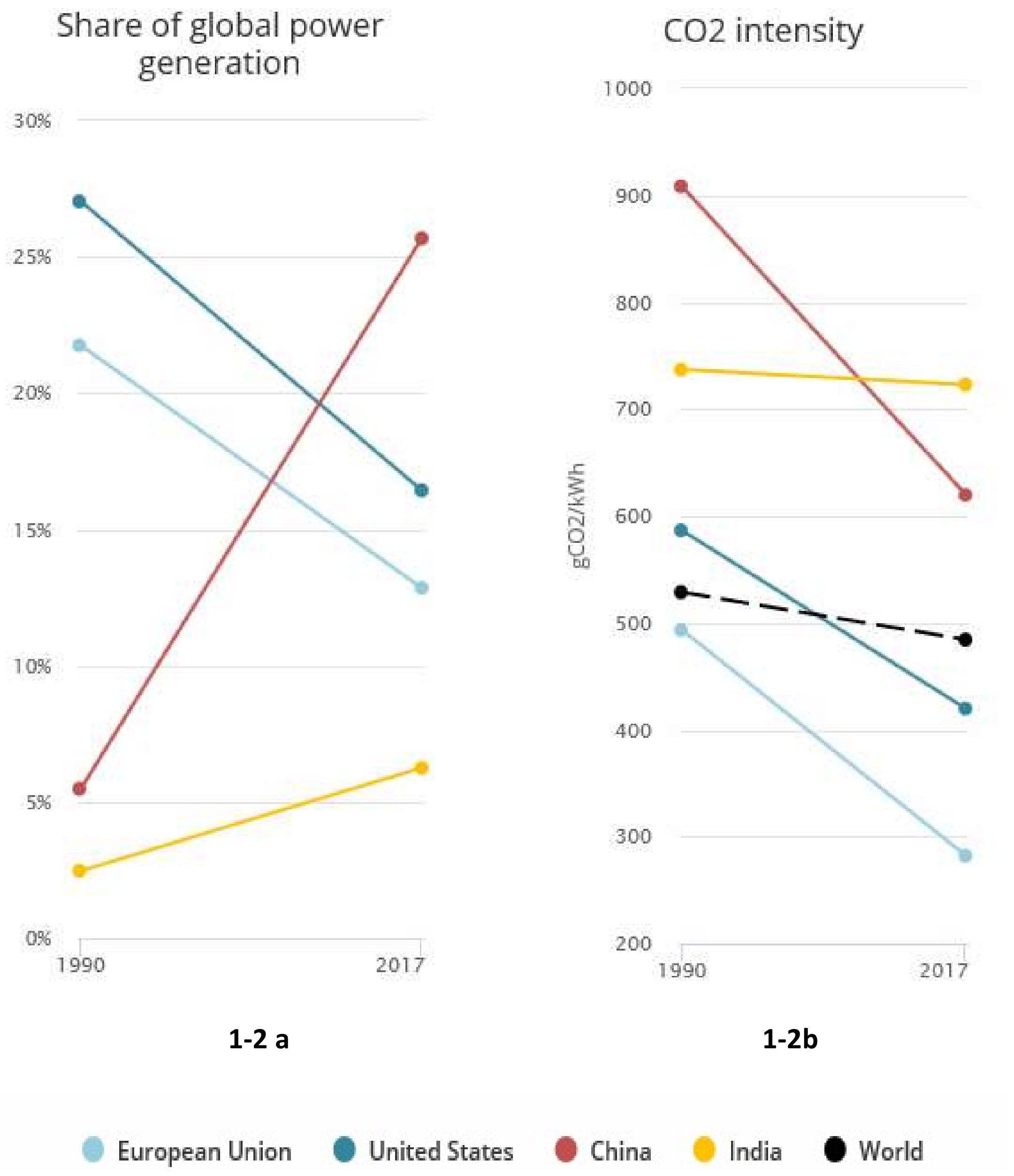
40,000 TWh by the year 2040 (Pavarini and Mattion, 2019). In view of this, emissions reported from electricity generation rose from about 6.3 $GtCO_2$ to 12.5 $GtCO_2$, almost doubling the initial value of 6.3 $GtCO_2$ reported (Pavarini and Mattion, 2019). Between 2010 and 2017, over 90% of global coal-fired power capacity (610 GW), were added from Asia alone, a value that is equivalent to the total installed coal-fired capacity in advanced economies and a resultant indicator of the high level of emissions reported from those areas during the period under consideration (Pavarini and Mattion, 2019). The fleet of power plants' addition depicts a high level of dependence on coal-fired power generation from two Asian countries, India & China, thereby leading to an increase of their roles in the global energy system as shown in Figure 1-2a.

However, in recent years, carbon intensity of largest economies (Figure 1-2b) were decreased due to reasons stated:

- Power plants efficiencies were improved in many regions;
- Fast reductions in costs of solar photovoltaic (PV) as well as that of wind turbines;
- Substantial policy support from governments, irrespective of rise reported in coal-fired power generation;
- Sources of energy generation gradually moving away from fossil fuels and
- Increase in electricity generation from low carbon sources by major electricity producers.

But as at 2017, there was a reported increase of global energy-related carbon emissions to a value of 32.5 $GtCO_2$ which was as a result of slow improvements in energy efficiency, coupled with higher energy demand (IEA, 2019a) as most countries are still dependent on electricity, whose generation is not near being decarbonized. Need to mention that, slow improvements in energy efficiency may lead to an increase in the overall cost of energy supply chain networks and with coal as the largest source of electricity generation, (38% as at the year, 2017), a 2.5% increment in CO_2 emissions from coal generation was reported, with emissions from coal constituting 80% of the increase reported (D'Ambrosio, 2019).

Further, with a 4% increase in global electricity demand in the year 2018 (to over 23,000 TWh) (IEA, 2019b) and 42% of energy-related CO_2 being associated with the power sector, CO_2 emissions from this sector should be a target for reduction consideration in order to achieve the outcomes for sustainable development scenarios, (SDS) (D'Ambrosio, 2019). With consideration given to Figure 1-2b, carbon intensities of major global energy players have greatly improved, but appreciable efforts are still reuired to meet climate goals.



1-2 a

1-2b

Figure 1-2 Share of a) global power generation and b) CO_2 intensity of global power producers (IEA, 2019b)

Notwithstanding the large share of fossil fuels in the current global energy consumption, the introduction and subsequent increments in the share of renewables sources of energy have proven to be a viable way of reducing the GHG emissions in the atmosphere (REN21, 2018).

It is worth noting that a substantial amount of GHG emissions on a global level occur as a result of energy production (Figure 1-3), with a value of about 78%, out of which 43% is from electricity/heat, and 11% from agriculture. Additionally, carbon dioxide emitted from fossil fuels and cement production, forestry and land use change, totals a value of 76% of emissions reported globally with methane and nitrous oxide contributing values of 16% and 6% respectively as shown in Figure 1-4 (Stats NZ, 2019).

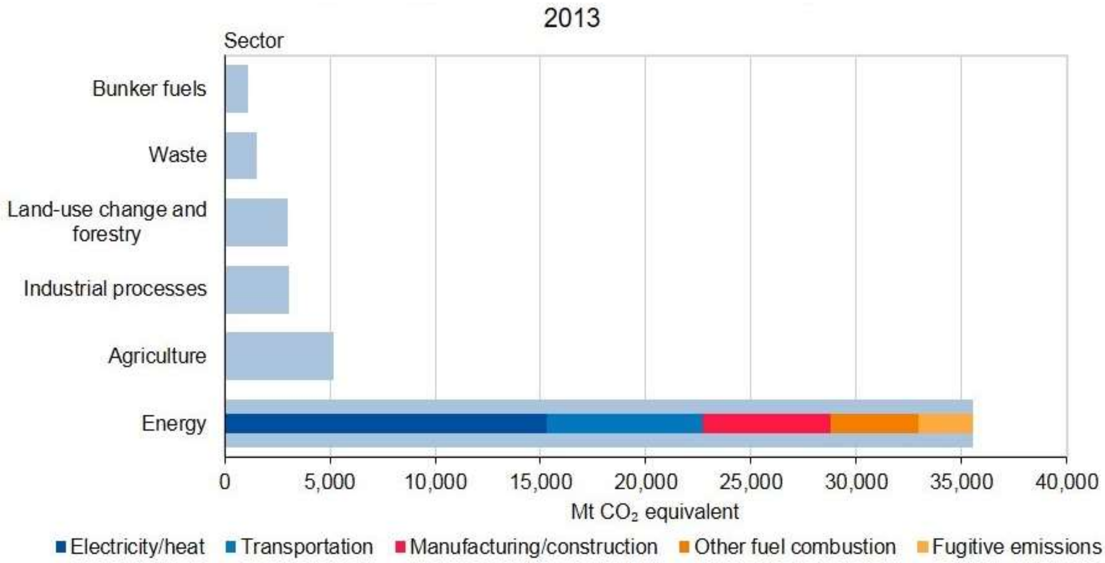


Figure 1-3 Sector categorization of gross global GHG emissions in MtCO2 equivalent (IEA, 2016)

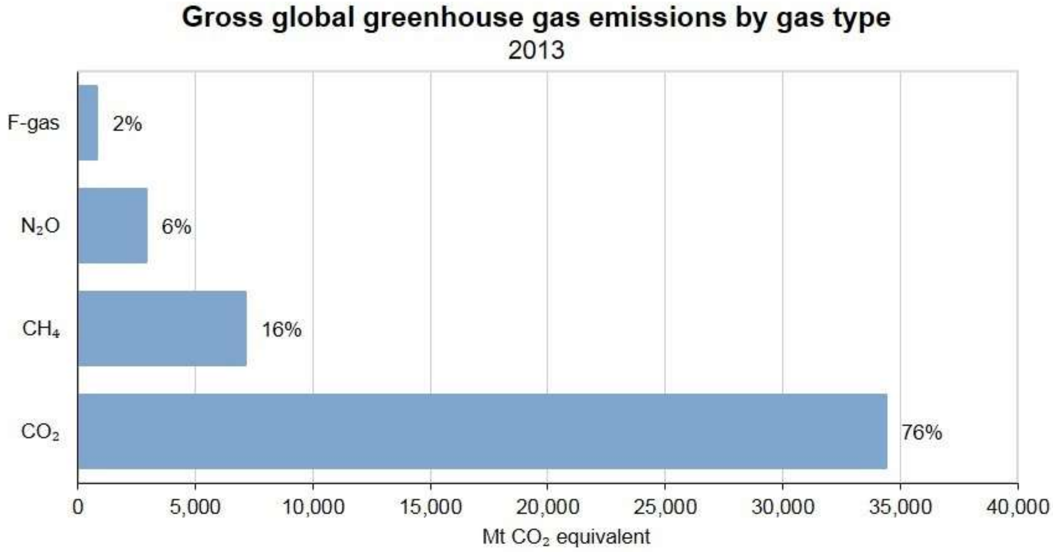


Figure 1-4 Gas type categorization of gross global GHG emissions in 2013 (IEA, 2016)

However, following the deployment of low carbon technologies with an increment of 6% which was offset by 2.6% increment in non-abated coal in 2018, strengths of emissions was reported to have reduced by 1.3%. Moreover, with the use of renewables (IEA, 2019b) obtained from sources such as wind, solar, hydro, geothermal and bioenergy, their integration into ESC networks, aimed at a gradual replacement of conventional fossil fuels for electricity generation, district heating, transportation and off-grid/rural energy services, REN21 (2018), will play a significant role in achieving the emission reduction targets over the next century.

Using the European Union (EU) as an example, and considering the 2030 package, which is a composition of legislation necessary for the EU to meet its climate and energy targets for the year 2030. It encompasses global EU targets and strategy aims for the period 2021–2030 (European Commission, 2014).

In essence, the package comprises three key targets: (i) achieving at least 40% reduction in GHG emissions from a base year of 1990; (ii) at least 27% of EU energy produced from renewables with a view of achieving 15% target on electricity interconnection after an existing target of 10% in the year 2020; (iii) achieving at least 27% improvement in energy efficiency (European Commission, 2014).

However, the set goals for renewables' share in the energy mix, as well as improvement in the energy efficiency, had an upward revision, to 32% and 32.5%, respectively, in 2018, furthermore, achievements realised from these set targets must be sustainable enough and lead to a pathway to achieve full decarbonisation by 2040 (CANE, 2019). Moreover, the target set by the EU for 2050 is a long-term one, with the aim of reducing GHG emissions by about 80–95% as compared to 1990 baseline (European Commission, 2018).

Regardless of these ambitious environmental targets, fossil fuels (coal, oil, and natural gas) still play an essential role in the current energy systems (Ritchie and Roser, 2018). Importantly, the use of fossil fuels results in the emission of carbon dioxide (CO_2), which is one of the main GHGs leading to global warming as these non-renewable resources have limited availability that influences the security of energy supply in the long term. Ultimately, this calls for an immediate action directed at balancing the role of energy in technological, social, economic and environmental development towards a transition to low-carbon energy sources (Ritchie and Roser, 2018). It is worth noting that, as at 2012, from the report published by National Oceanic and Atmospheric Administration, NOAA, (Figure 1-5), earth is still absorbing about half carbon dioxide emitted into the atmosphere by human beings (anthropogenic emissions) and this is done through land ecosystems and by the oceans. This value however, needs reduction by year 2030/2050 as reported by SDS.

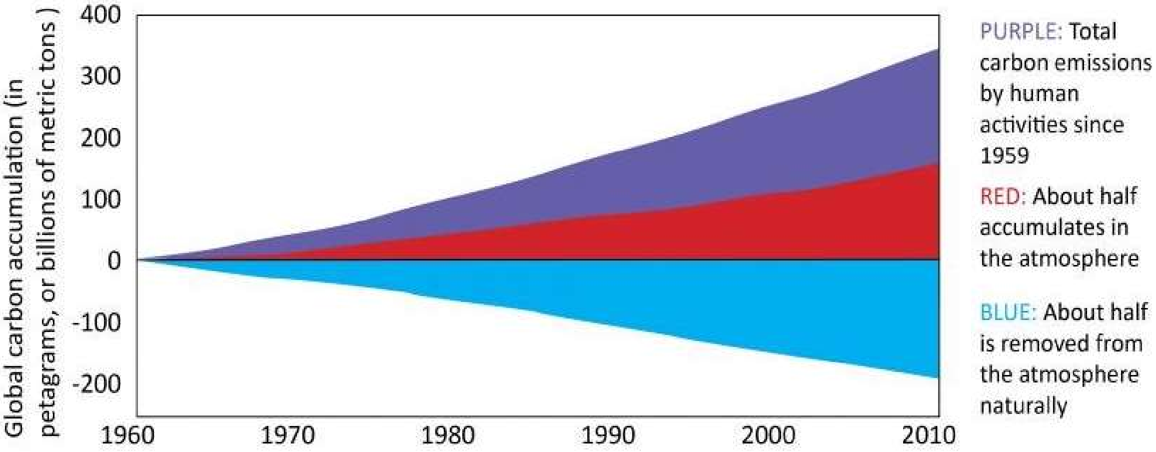


Figure 1-5 Carbon accumulation on a global basis (NOAA, 2012)

Further, report has it that, the contribution of bioenergy to world primary energy in the future could be between 25% and 33%, a value that could be up to 250 EJ by the year 2050. In as much as bioenergy can be used in producing heat, electricity and transport fuels, it usage has its inherent challenges. Issues around land competition, logistics and its use for other products must be managed properly, as well as its conversion processes undergoing extensive innovation. These processes, if well managed, should build the confidence of the general public as well as policy makers on having a sustainable expansion on bioenergy (IEA Bioenergy, 2019).

Therefore, in order to achieve global decarbonisation, emissions reduction as well as power generation is of utmost importance Pavarini and Mattion (2019), as such, a thorough co-ordination of processes and operations in the design and planning of ESC is of utmost importance.

1.2 Motivation

An increase by 3% in the year 2018 was reported for power generation from coal, having a similar percentage increment to the value reported in 2017 and surpassing the 10,000 TWh level. In view of this development, electricity generation from coal-fired power plants is responsible for about 38% of global electricity generation, thereby representing the biggest source of global power generator (D’Ambrosio, 2014)

Renewables' share in global electricity generation is 25%, natural gas has a value of 23%, while energy from nuclear sources is 10% and that from oil has the least share of 4% (Figure 1-6).

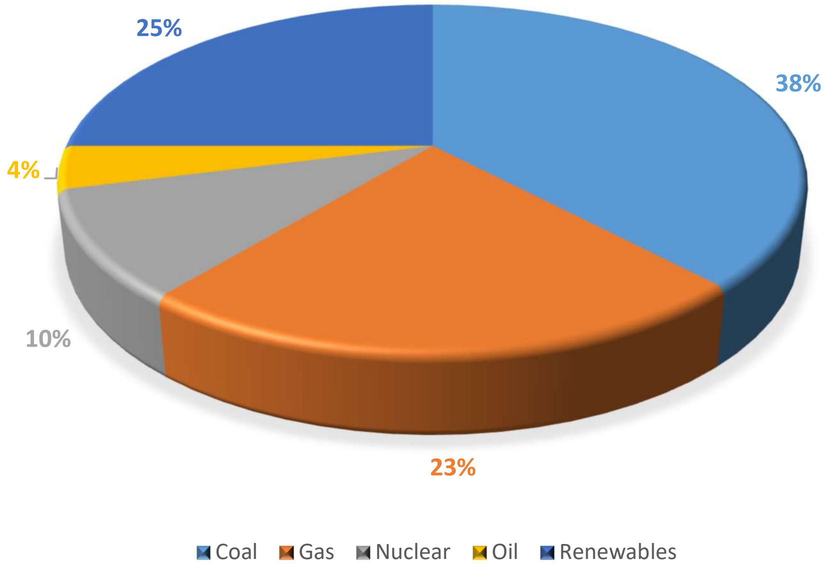


Figure 1-6 Distribution of global electricity generation sources for the year 2017 (Petrova, 2018)

As such, accompanying emissions from coal-fired power plants amount to about 30% of CO_2 emissions globally, in addition to their characteristics low efficiencies (about 33%$_{LHV}$), indicating their high level of contribution to global CO_2 emissions (IEA-ETSAP and IRENA, 2013). If this trend continues with no intentional deployment for technologies to tackle emissions, then, climate change will be unavoidable and this poses a threat to the world in total.

According to SDS, changes need to take place in the global energy system for climate change to be tackled, attain universal energy access and improve air quality. These changes, however can be incorporated during the process of designing and planning of energy supply chain networks. But from reports by new policies scenario (NPS), it clearly shows that, the world is nowhere near the track as indicated in Figure 1-7, with the power sector accounting for 42% of all energy-related CO_2 emissions, the attainment of the SDS outcomes by the power sector is highly essential (D'Ambrosio, 2014).

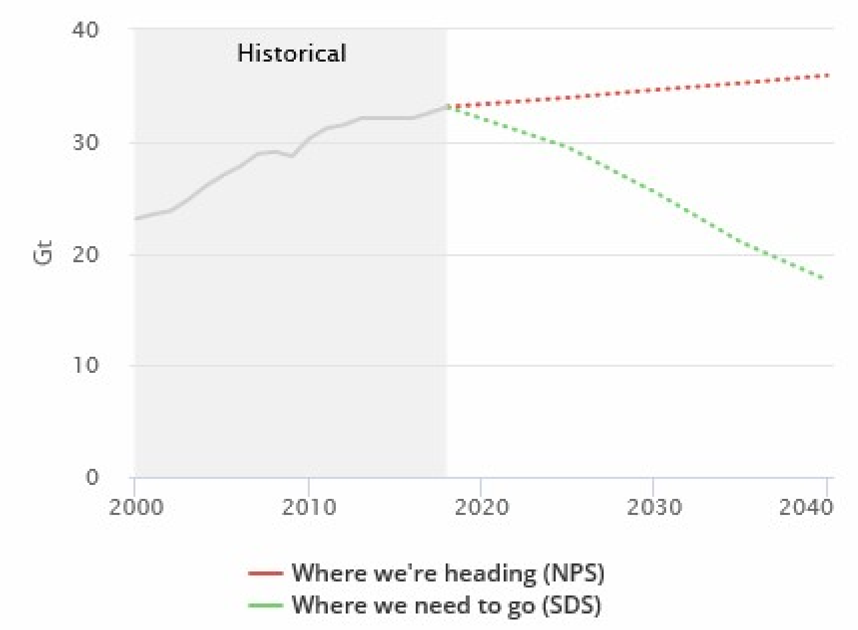


Figure 1-7: Energy-related CO_2 emissions (IEA, 2018b)

Yet, aspirations to achieve the CO_2 emission reduction targets, which were provisioned in the Paris agreement, United Nations Climate Change, (2015) may be difficult to meet. This is evident from preliminary data revealing that CO_2 emissions output obtained from processes involving fossil fuels, in addition to those from industry reported a 2.7% increment in the year 2018, indicating the highest increase reported over a seven year period. As such, optimization-based approaches for the design and planning of energy supply chain networks, resulting to the attainment of ESCs, having all the attributes mentioned are presented. Moreover, to achieve substantial shift towards renewable energy sources for emissions reduction , integration of biomass into the existing ESC networks should be considered (Duarte et al., 2014). The key advantage of biomass is the fact that, it is considered as a versatile energy source as it can be converted into heat, electricity and fuels. Furthermore, it is also one of the renewable energy sources that is capable of generating energy on demand Rentizelas et al. (2009); hence, its consideration as a non-intermittent energy source. This attribute of biomass can be a solution to the variability of other renewable energy sources, such as wind and solar energy.

Furthermore, with continuous demand for energy at an affordable cost and reliable supply, all available resources should be harnessed efficiently and integrated into ESC networks (Sharma et al. 2013). This implies the achievement of a well-structured ESC which is characterised by an optimal energy supply pathway, obtained at a minimum possible cost and emissions, translating into overall profits, on the economic, environmental and social aspects for all stakeholders represented on the supply chain.

Additionally, in consideration of the long-term goal of complete decarbonisation of the power sector, achieving the set goals is still not possible in the long run, but, appropriate steps, taken could serve as a short term precautionary measure directed towards this achievement. Bearing this in mind, the integration of biomass into the design and planning of ESC networks has numerous advantages aimed at moving the global economy towards achieving the set targets of reducing atmospheric emissions and also towards a fully decarbonised global economy.

Recent report on tracking clean energy shows bioenergy, such as, wood, wastes having organic derivations and agricultural materials as well as renewable energy from natural sources which are replenished continuously, such as, sunlight, wind, rain, tides and geothermal heat, needed more efforts in its implementation bid at moving closer towards the goal of achieving clean energy, while coal on the other hand, was depicted as not being on track (IEA, 2019e).

In addition, SDS has created a mode and an opportunity of achieving the combination of three well thought out goals, as stated below (IEA, 2019d)

- Keeping the Paris Agreement on climate goal adequately below 2°C, by dealing with climate change (SDG 13);
- Achieving global and universal access to energy (SDG 7) and
- Considerable reduction of air pollution with its reduction on severe health impact (a component of SDG 3)

which are considered crucial and are energy-related SDGs. Further, in order to move steps closer to the set goals on reducing atmospheric CO_2 emissions, increasing the level of renewables in the global energy mix is considered as well as the determination of effective strategies could be put in place. Additionally, perceptions of individual consumers on the demand side of the ESC networks are considered.

Over the years, contemporary energy networks have been undergoing continuous improvement to reduce the consumption of fossil fuel and emissions of GHG to the environment (Ba et al., 2015) .This, no doubt, can be achieved by employing sustainable energy material resources which ultimately leads to the overall improvement in the efficiency of the energy system.

While a sufficiently great research effort has been committed to biomass production and its conversion processes, the important role that logistics play in its supply chain network cannot be overlooked, nevertheless, sufficient quantities of biomass and at reasonable prices are required at conversion facilities. Further, this will involve large territories and a great number of biomass producers. For efficiency of the approach stated, use is made of quantitative models in order to analyse, evaluate and optimize all resources and various levels of their requirements. This includes, energy material resources and generation, associated costs, processes and technologies involved, energy demand and consumption, as well as environmental impacts.(Ba et al., 2016)

With sustainability being an important factor worthy of consideration in the design and planning of ESC networks, its development entails meeting humanity's current needs by integrating and using reasonably natural resources, environmental protection, economic prosperity and quality of life, without any compromise made on the future generation's ability to meet their own needs.

In as much as biofuel production may lead to an increment in economic development by attracting investors and increasing farmers' income by shifting focus on biomass resources that are otherwise not used, there still exist problems raised by the society, such as, its acceptability, land use, impact on rural population, pathway for job creation and poverty reduction.

With further consideration given to biomass which is a known to be a low density material that could be lost during transportation from its original place of harvest or collection to an intermediate point of conversion or usage, a need for an improved and effective supply chain is inevitable (Athanasios et al. 2009). However, for biomass integration in an existing ESC network to be worthwhile, the energy materials in use should be sourced locally, this is necessary because local sourcing of biomass materials can result to shorter supply chains with a higher predictability of delivery times and at reduced costs and GHG emissions. Additionally, the biomass supply chain (BSC) is characterised with a range of uncertainties, such as weather, seasonality, physical and chemical characteristics, biomass suppliers and their willingness to grow biomass crops, transportation and distribution infrastructure, supplier contracts and government policies (Sharma *et al.*, 2013). Moreover, different types of biomass resources, such as energy crops, agricultural residues, municipal solid waste (MSW) and forest residue make use of customized equipment for their collection, handling and storage, further increasing the level of complexity of the supply chain, which invariably is a determining factor in investments and operational costs. This also affects the design and planning of the supply chain networks (Rentizelas et al. 2009). Therefore, in order to have efficient BSCs/ESCs, the design in combination with adequate planning must be implemented optimally with the material resources undergoing some conversion processes before the end products can be used effectively by consumers.

In view of the second research gap stated above and with specific focus on energy targets set by the European Commission, of which the UK is represented at the moment, appreciable strategies should be put in place for achievement of the set goals. Moreover, in order to fully realize the benefits from the impact of the set targets, an extensive analysis of practices and their effects of all stake holders involved is required, which leads to the identification of the third research gap.

Furthermore, with the main goal of the energy policy in the UK's focus on complete decarbonisation in the economy by utilising sustainable energy material resources, increasing energy production efficiency and security and supplying energy, including electricity and heat to end users at a reduced and affordable cost is highly important. However, for the stated objectives to be achieved, there is the need to also consider individuals represented on the demand side of the ESC networks.

1.3 Aim and objectives of the research project

The aim of this research is the development and application of optimization-based approaches on energy supply chain networks (ESC) for the minimization of overall costs of the supply chain as well as costs of emissions and also propose strategies that will promote renewable energy embracement in ESC networks. In order to achieve this aim, the following objectives for this research project have been established and addressed:

i. Conduct a general review on processes involved in the design and planning of energy supply chain networks.
ii. Conduct a detailed review on optimization models on energy supply chain networks.
iii. Develop a new optimization model for simultaneous operations and maintenance planning of processes in combined heat and power plants.
iv. Formulate optimization models for the integration of biomass into energy supply chain networks.
v. Conduct a survey on targeted UK individuals' energy generation and usage to reflect strategies that will promote increased level of renewables embracement in the existing UK energy mix.

1.4 Novelty and correlation of project outputs

In a drive towards the realization of the established objectives for this research project, a number of contributions to the scientific body of knowledge are hereby identified. Firstly, in most cogeneration plants, processes, such as operations, energy production planning and maintenance are performed in a sequential manner. This implies that, in most power plants operations, after a process such as energy production, then, maintenance planning can follow, this otherwise conventional method, is not only cost ineffective, but also, highly computationally demanding. As such, the efficiency level of the Karaganda utility system (KUS) power plant, whose energy production and maintenance processes follow a sequential approach is lower in comparison to when simultaneous approach, which has been implemented in the course of this research was followed. In this approach, all processes that have been identified for the smooth running of the power plants were operated and optimized concurrently. It is worth mentioning that, the lower efficiency predicted in the conventional/sequential approach is due to frequent starting up and shutting down of the power plants, resulting to higher use of energy resources, such as boiler fuel as well as power plants' internal electricity and heat usage and also on costs related to its fixed operation.

In the demonstration of both sequential and simultaneous approaches of process operations and maintenance planning of a large scale combined heat and power (CHP) plant, the annual total cost of the CHP plant was reduced by a value of 21% with complete avoidance of turbines operating in extreme regions for the simultaneous optimization approach.These extreme regions have been defined as regions above 100% and below 60% of the turbines' desired operating region. In essence, the energy and resource efficiency of the power plant has been enhanced by the simultaneous approach. Additionally, the solutions predicted an appreciable reduction in startup/shutdown costs (85%) as a result of a corresponding reduction (15%) in the boiler fuel costs, which was achieved by simultaneous operational and maintenance planning approach utilized on the coal-fired cogeneration plant and avoidance of unnecessary startup/shutdown actions on the plant. Also, a 13% reduction in the fixed operating costs was obtained. Overall, the comparative case study clearly shows that the proposed simultaneous approach is an effectual means for generating optimal production and maintenance plans. In contrast to the conventional/sequential approach that has originally been in place at the KUS, the optimized solution satisfies the energy demands in all periods. More importantly, the proposed optimization framework could readily be applied to other cogeneration plants with similar plant structure.

Although fossil fuels play a significant role in the current global energy portfolio, their limited availability and links to geopolitical uncertainties pose a threat to the global energy security. Therefore, innovations aimed at integrating renewable energy sources into ESC networks need to be deployed at a scale in a cost-effective manner. The formulation of efficient optimisation models to support the design of effective ESC networks is critical to meeting the greenhouse gas emission reduction targets. Moreover, integrating renewables such as biomass into energy supply chain networks, aimed at a gradual replacement of conventional fossil fuels for electricity generation, district heating, transportation and off-grid/rural energy services, REN21 (2018) will play a significant role in achieving the global emission reduction targets. Importantly, CO_2 emissions from energy-related processes and operations increased by 1.7% between 2017 and 2018, reaching 33.1 $GtCO_2$ in 2018. This increase resulted mostly from the combustion of fossil fuels in the power sector which constituted almost two-thirds (~350 $MtCO_2$) of the CO_2 emissions growth. Moreover, in Asia, the utilisation of coal in the power sector exceeded 10 Gt CO_2 (IEA, 2018a), which accounts for 30.2% of the global energy-related CO_2 emissions. As a result, it is becoming even more challenging to meet the emission reduction targets set out in the Paris Agreement that are a legally binding set of environmental targets. These cap global warming to a value less than 2°C greater than that of pre-industrial levels, with a desire for its reduction to 1.5°C (EC, 2015). Nevertheless, it is essential to note that the growth in CO_2 emissions was 25% lower than that of the energy demand in 2018, mostly due to the deployment of low-carbon technologies such as renewable energy sources and nuclear, as well as gains reported from energy efficiency. In 2018, 215 $MtCO_2$ emissions were avoided as a result of switching to renewables in the power sector (IEA, 2018a). Although this trend is promising, the rate at which low-carbon technologies are implemented in ESC networks may not be sufficient to meet the desired emission reduction targets. Therefore, pathways for their cost-effective implementation need to be derived. As a consequent of this derivation (integrating biomass into energy supply chain networks), annual total emissions level was reduced by a value of 4.32%. However, the percentage composition of biomass that predicted an appreciable reduction in the emissions level ranged between 5–8%. Yet, in the considered ESC, a 4.57% increase in the total cost of the energy supply chain network was predicted at a biomass fraction in the mixed fuel of 7.9%, with the fixed cost having the largest impact on the total cost of the ESC network. Consequently, it is evident that the cost increment obtained in the co-fired plant can effectively be offset by cost reduction obtained from emissions using the state-task network approach and based on the applicability of effective carbon tax legislations.

From the responses obtained from the energy survey and analysis conducted, it shows that a huge impact will be achieved on renewables' energy embracement if incentives are in place for renewable energy generation and usage. Additionally, policies surrounding solar energy generation, such as solar tax credit could be improved upon as evident from appreciable percentage (49.41%) obtained from target respondents. Also, there should be a raise in consumer awareness on inherent benefits of economic, environmental, social and health areas that are associated with renewable energy generation and usage. This could be achieved with the use of the internet, social media (by creating blogs that address different aspects of renewable energy), use of posters, fliers, bill boards, television and radio adverts. Moreover, there should be an introduction of a fair, stable and working financial incentive policy for an appreciable number of years on the demand side (individual consumers) of the supply chain, such as Individual Renewable Energy Usage Tax Credit (IREUTC).

Finally, policy makers could introduce varying energy mix on new buildings going forward. In view of the last proposition stated, a proportion of household heat and power generation sources from renewable energies could be introduced instead of overall households' gas and electricity supply from non-renewables sources of fuel.

1.5 Outline of PhD thesis

The structure of this thesis has been arranged to revolve around five objectives that were identified in Section 1.3 and made up of six main components: Chapter 1, is the introductory chapter, while Chapter 2, includes the literature review. Chapters 3, 4 and 5 considers all methodologies that have been employed in the different case studies in the project. Chapters 6, 7 and 8 deal with analysis of the results/findings on the case studies considered. Chapter 9 considers general discussion on the research outcomes, while, conclusions and recommendations for future work are presented in Chapter 10.

In Chapter 1, previous and current observations, views, perceptions and experiences as regards ESC networks that give consideration to the existence of the problems inherent in the ESC networks are presented. Opinions on fossil fuel ESC networks as well as renewables supply chain networks are considered. Additionally, strategies to promote an increased level of renewables' embracement in ESC networks are considered, with focus on target groups drawn from some counties in the UK. Motivation for the research work was stated and the aim as stated in Section 1.3 has been developed in order to showcase the existence of the problems surrounding ESC networks with efforts made to contribute solutions to the identified problems. The aim is supported by objectives, which have been completed in order to achieve the stated goals.

Chapter 2 gives a comprehensive review of related literature, with consideration given to critical analyses on works, observations, findings, design and methods used by other researchers on ESC networks, with further descriptions given to optimization models for the design and planning of ESC networks. Finally, a study into the policies on the EU energy roadmap was carried out with a study on various surveys conducted by researchers on energy generation and usage. It is worth mentioning that, energy survey with a mixed model of both quantitative and qualitative questions that centres on energy generation, usage, type and awareness level was conducted with target respondents obtained from some counties of the UK.

Chapter 3 describes the theory of energy production and maintenance planning in a large-scale CHP plant, also, methodology employed in the design and planning of energy supply chain networks is presented. Here, a new optimization model for the simultaneous planning of energy production and maintenance processes in a combined heat and power plant was developed and solved for total cost minimization with the use of the GAMS software. Moreover, analysis of the results on simultaneous energy production and maintenance planning of combined heat and power plants, focusing mainly on the case study of the largest cogeneration plant in Kazakhstan, otherwise known as the KUS was included. For this case study, a detailed comparison is presented among the solutions obtained by the proposed optimization approach and the solution implemented by the industry (i.e. KUS CHP plant). More specifically, solutions, analysis and comparison of different solution approaches of the KUS, optimized case 1 (OPT-1), optimized case 2 (OPT-2) and optimized case 3 (OPT-3) were conducted and all optimization problems solved and the model validated through the implementation of results obtained and presented to the management of the power plant.

In Chapter 4, optimization model for integrating biomass into a coal-fired energy supply chain networks was formulated using the state task network approach (STN) and same implemented and solved with the use of the GAMS software for emissions reduction. Chapter 4 also includes analysis of the results obtained on integrating biomass into a coal-fired ESC network is presented, the case study focused on the energy state task network (ESTN) for determining emissions reduction in the co-fired plant and the model was validated against data obtained from literatureIn

Chapter 5 considers a combinationmix of both quantitative and qualitative energy survey model questionnaires were developed and same distributed to consumers, who are residents of the UK with the aim of proposing strategies that will promote improvement in the level of renewables embracement in the UK energy mix. Furthermore, analysis/results for strategies proposition for renewables embracement in the UK energy mix with the use of Qualtrics online survey tool is presented, while in Chapter 6, a general discussion is presented on the case studies considered in the course of this research, in addition to recommendations for future studies and finally, conclusions are presented in Chapter 7.

1.6 Dissemination from the PhD thesis

1.6.1 Journal and conference publications

Kopanos,G.M., Murele, O.C., Silvente, J., Zhakiyev, N., Akhmetbekov, Y and Tutkushev, D. “Efficient Planning of Energy Production and Maintenance of Large-scale Combined Heat and Power Plants”, Energy Conversion and

Management, 169 (2018) 390-403, doi: https://doi.org/10.1016/j.enconman.2018.05.22

Murele, O.C., Zulkafli, N.I., Kopanos, G., Hart, P., Hanak, D. “Integrating Biomass into Energy Supply Chain Networks”, Journal of Cleaner Production, 248 (2020) 119246, doi: https://doi.org/10.1016/j.jclepro.2019.119246

Murele, O.C., Zulkafli, N.I., Hanak, D., Kopanos, G. (2018), “Integrating Renewables in Energy Supply Chain Networks”, Proceedings of 7th International Conference and Exhibition on Clean Energy, Quebec, Canada, available online: http://icce2018.iaemm.com/ .

1.6.2 Conference and workshop presentations

i. Oluwatosin Christiana Murele., “Optimal Energy Dispatch and Maintenance of an Industrial Coal-Fired Combined Heat and Power Plant in Kazakhstan”, 9th International Conference on Applied Energy (ICAE 2017), 21st -24th August, 2017, held at Cardiff University, Cardiff, UK.

ii. Oluwatosin C. Murele., “Integrating Renewables in Energy Supply Chain Networks”, 7th International Conference and Exhibition on Clean Energy (ICCE 2018), 6th-8th August, 2018, held at Laval University, Quebec, Canada.

iii. Workshop on Qualitative Research Methods, Northampton University, United Kingdom (UK), 4th July, 2017.

2 LITERATURE REVIEW

2.1 Energy generation, demand and policies

2.1.1 Global energy mix

An increment of 8,453 Mtoe was reported in global total primary energy supply (TPES) between the years 1971 and 2007 with the most visible changes occurring in relative shares of oil and gas supply. In spite of the 12% reduction (from 44% to 32%) reported on oil supply, it nevertheless, remained the energy supply source with the largest share in 2017 (IEA, 2019f). Natural gas was reported as having a 6% increment within the specified period, while coal's share was reported to have a 1% growth. However, during the period considered, coal had remarkable fluctuations but continuous increase between 1999 and 2011, while energy supply from nuclear source reported a growth of 4.4% (D'Ambrosio, 2014) as shown in Figure 2-1.

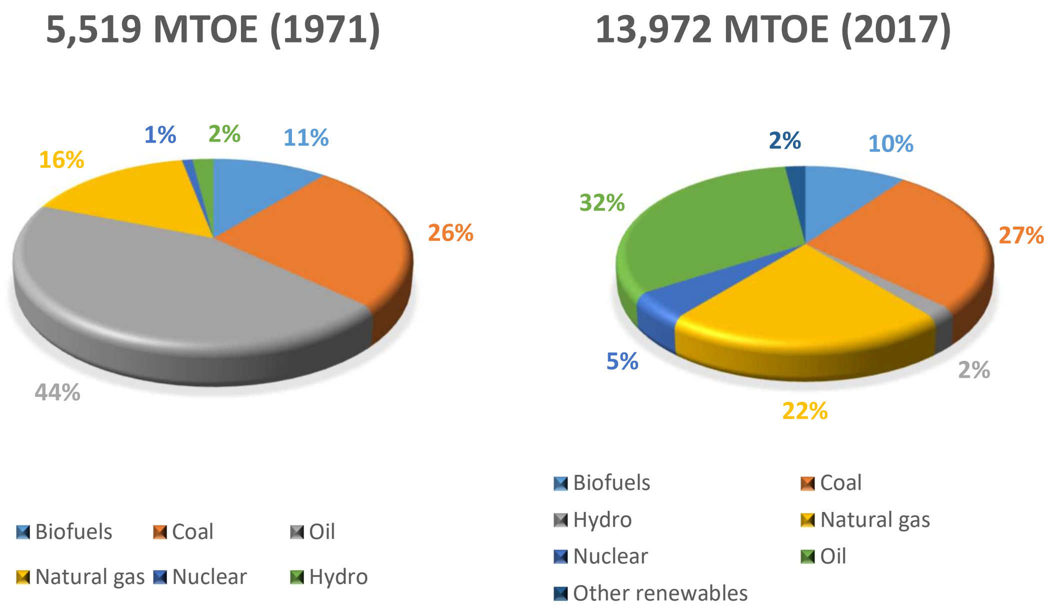


Figure 2-1 Global total primary energy supply fuel-wise (IEA, 2019f)

Moreover, from a comparison of global energy consumption (Figure 2-2) with data available for the total primary energy supply (TPES), it is evident that there are discrepancies in both figures for different energy sources. However, this is due to the amount of energy which is lost while converting from one form of energy to another and also that which is lost due to transportation from the points of generation to points where they are demanded by the consumers/end users.

To further illustrate this, in the year 2014, the total for world primary energy supply was 155,481 terawatt-hour (TWh), while the world's total energy consumption was, 109,613 TWh, which is equivalent to a reduction of 29.5% when world primary energy supply is compared with world's total energy consumption (IEA, 2017).

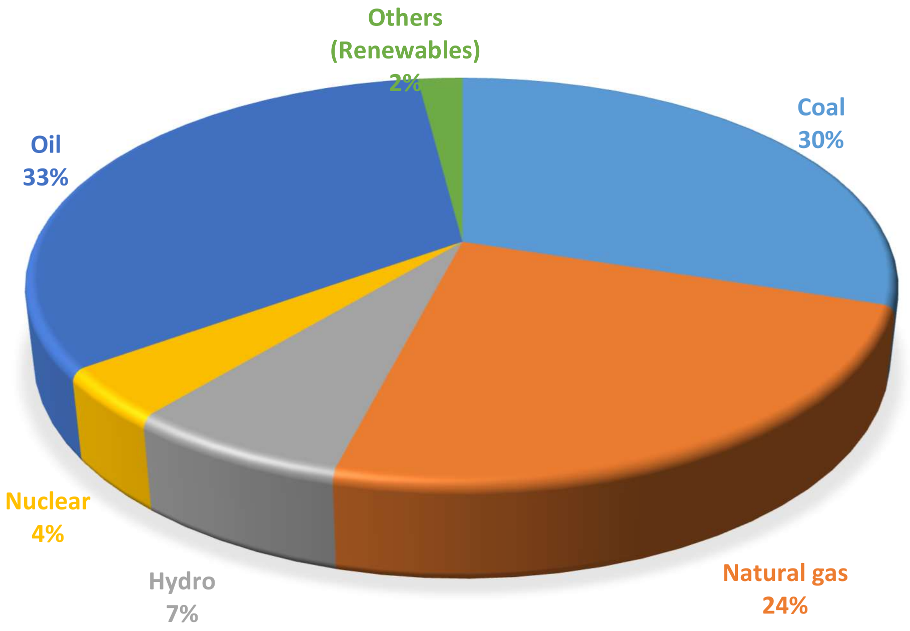


Figure 2-2 World primary energy consumption fuel-wise (2014) (IEA, 2017).

Furthermore in 2016, the composition of the world's total energy that was obtained from fossil fuels was 80%, biofuels contributed 10%, the percentages on nuclear source and renewables (inclusive of wind, hydro, solar and geothermal) were 5% respectively, however, the percentage of the world's total energy that was used in electricity generation was 18%, while the outstanding of 82% was utilized for heating and in the transportation sector (IEA, 2018c).

However, by the year, 2018, global energy consumption had an increment that doubled the average rate of growth since the year 2010 IEA (2018b), while emissions from CO_2 was increased by 1.7% in the year 2017. In view of the increase reported in emissions in 2017, a new record on CO_2 emissions was set IEA (2018a) with renewables not meeting the targets on electricity demand in that year (IEA, 2018b).

Biomass, having the potentiality to reduce, to an appreciable extent the effect of these emissions, need to go through optimization techniques for optimal pathways to be achieved. During optimization , all pillars of sustainability, ranging from economic (profits), environmental (planet) and social (people), depicted as the '3Ps' of sustainability need to be addressed (Cambero and Sowlati, 2014). More often than not, the consideration of uncertainty in BSC networks is imminent as in the modelling of BSC with the use of stochastic mixed integer linear programming (MILP) (Osmani and Zhang, 2014). This is due to the fact that, biomass, has attributes such as, seasonal seasonality, demand and supply variabilities as well as complexities in its supply chain. Moreover, in the work of Osmani and Zhang (2014), uncertainties considered were in biomass and biofuel demand, their supply in addition to prices associated to each of the energy material resources as well as energy products.

Gielen *et al.* (2019) explores the techno-economic attributes of momentum gain in energy transition to year 2050, by incorporating new sets of data for renewable energy. In their work, they came up with a proposition that, efficiency in renewable energy as well as renewable energy technologies (RETs) were the core components of that transition. Undoubtedly, support for decision making and operations' enhancement at all levels have resulted in the development of diverse supply chain models. They went further to propose an article targeted on modelling the strategic to tactical decision making hierarchy in a supply chain model and showed that decisions, ranging from economic, environmental, social, technological, operational, tactical, routine and strategic are derivable from suitable and appropriate supply chain models (Lainez-Aguirre and Perez-Fortes, 2015).

Accordingly, a bi-level mathematical model was presented by Cakravastia et al. (2002), the objective was the ultimate selection of supplier in the design of their supply chain networks that will minimize discontentment of customers and measured by two performance indicators, namely, price and delivery lead time.

2.1.2 The EU energy roadmap

Government of different countries, no doubt are amongst the drivers for green or renewable energy utilization as their inclusion in the present energy mix cannot be underestimated. Although, this is achieved through various policies, key of which are the 2020, 2030 and 2050 climate and energy frameworks which are applicable in the European Union. Notwithstanding the targets of these strategies, adequate incentives must also be put in place to change the course of energy generation. Considering the 2011 Energy Roadmap set out by the European Commission, four major routes have been identified as drivers towards a more supportable, comparable and assured energy system by the year, 2050 (European Commission, 2014b). The identified routes include, energy efficiency, renewable energy, nuclear energy as well as carbon capture and storage.

Additionally, other stake holders include, market and competitors, companies, individual consumers' initiatives and awareness as well as support for renewable energy at the national level. It is interesting to note that at the local level, there exists some form of resistance to renewable energy embracement (Howard *et al.*, 2013) Despite the resistance, the EU roadmap shows conformity with EU member states' ambition to generate a significant source of their energy supply from renewable energy sources (Figure 2-3).

From the analysis stated, the conclusions drawn around the roadmap centre on:
- Energy system decarbonisation, which has proven to be achievable, both technically and economically as pathways for meeting emissions reduction targets are cheaper than continuation of policies that are obtainable at the moment (Figure 2-4).
- Efficient use of energy in addition to increment in the share of renewables are critical in the energy mix**.**
- Replacement of an appreciable number of infrastructure that were built in the EU about 30-40 years ago should be done with alternatives having low carbon

attributes, as the International Energy Agency has reported that, after 2020, power sector investments will cost 4.3 times as much as those made before the year 2020.

- Additionally, in comparison to individual national strategies, a collective approach (European) should lead to the achievement of reduced costs and increased supplies of energy. This is due to the fact that, as long as the energy market is a common one, energy can be produced at the cheapest locations and supplied to locations where it is needed (European Commission, 2014b).

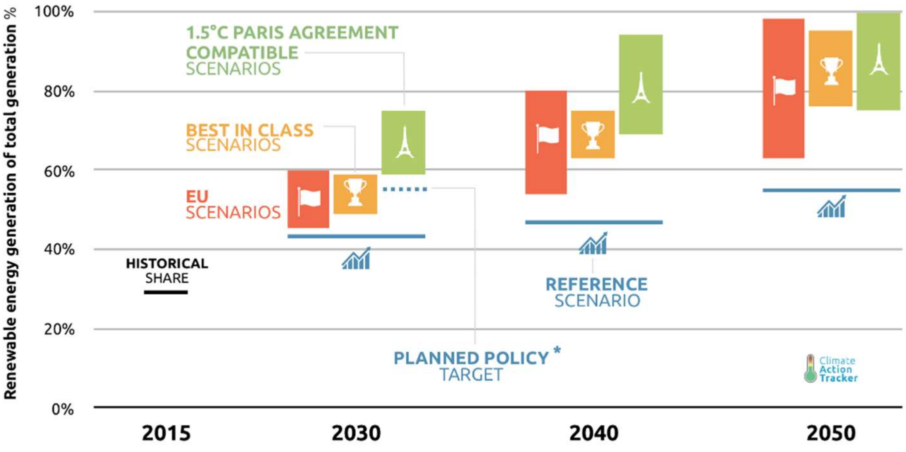


Figure 2-3 Share of renewable energy in total generation considering electricity sector scenarios (Climate Action Tracker, 2018)

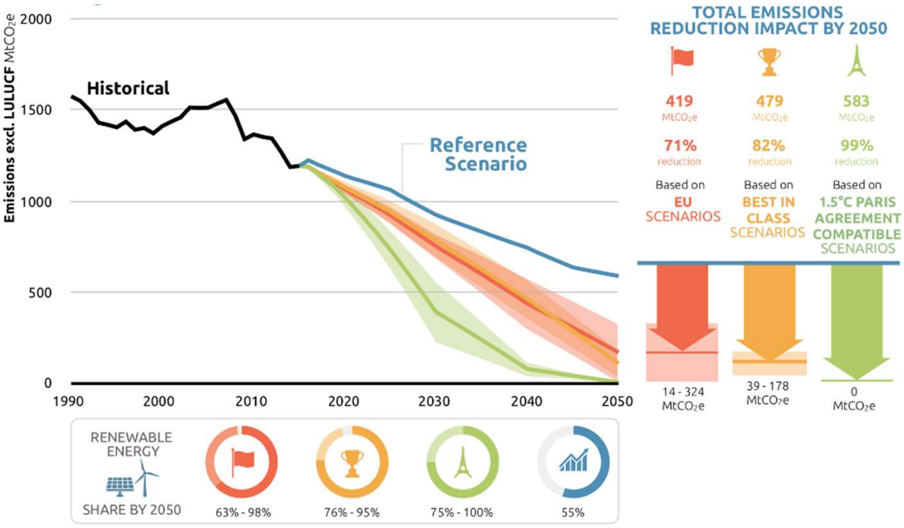


Figure 2-4 Potential emissions reductions in the electricity sector by year 2050 (Climate Action Tracker, 2018)

2.1.3 The Montreal protocol

The Montreal Protocol was signed into agreement in 1987, with its focus majorly on substances that deplete the ozone layer. These substances include chlorofluorocarbons (CFCs) and halons and are also termed as halogenated hydrocarbons containg chlorine and bromine, with N_2O not included (United Nations, 2012). Moreover, these compounds, which are identified as ozone depleting substances (ODS) are categorized into two groups, class I ODS, which consist of chlorofluorocarbons (CFCs) and class II ODS consisting of hydroclorofluorocarbons (HCFCs). Its coming into effect witnessed a reduction in the production, consumption and eventual emissions of these substances (Velders et al., 2007). Moreover, these ozone-depleting substances can also be referred to as GHGs, whose emissions contribute to climate change. Yet, report has it that, protection on the climate that was solely achieved by the Montreal Protocol outweighs the target for the first period of commitment on the Kyoto protocol. Velders et al. (2007) further stated some advantages of the Montreal Protocol over the Kyoto Protocol; including the management of substitute's fluorocarbon's emissions and the use of substitute gases having lower potentials of global warming.

2.1.4 The Kyoto protocol

Considering the Kyoto protocol, it requires that all participating nations take appropriate action to reduce their collective GHG emissions by 5.2% below the respective 1990 levels, during the period 2008-2012. The target actually revolves around the overall reduction of emissions from six GHG, namely: carbon dioxide, methane, nitrous oxide (N_2O), sulphur hexafluoride, HFCs and PFCs (UNEP, 2008). The set target of the first phase of the Kyoto protocol has been achieved by the EU and all states within its territories, while all efforts has been geared towards attaining the target of the second phase which is a period between 2013-2020 (CANE, 2019).

Although both the Kyoto targets and EU 2020 targets basically entails the reduction on emissions, however, there still exists differences as regards to various components of the economy that constitute this reduction (CANE, 2019).

With the sectors for emission reduction covering international aviation in the 2020 policy, European commission (2007), for the Kyoto protocol, the sectors included are land use, land use change and forestry (LULUCF) (CANE, 2019), with the base year for the Kyoto protocol is not 1990 as it is with the EU 2020 target. For the Kyoto protocol, an average emission reduction level of a value below 20% is required and expected over the second phase target years (2013-2020).

2.1.5 The Climate Change Act 2008

The Climate Change Act 2008 originates from the Parliament of the UK, where the Secretary of State has the responsibility of ensuring that the account of the net UK carbon emissions for all six Kyoto GHG gases for the year 2050 is at least 80% lower than those obtained in the year 1990, as a strategy for the avoidance of dangerous climate change (Pielke, 2009). In essence, the six Kyoto gases include, carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulphur hexafluoride (SF_6) as well as Nitrogen trifluoride (NF_3). It is worthy to note that, renewables' share in electricity generation in the UK increased to 33.3% in 2018 (111TWh) as a result of increased capacity in renewables' shares in the energy mix.

2.1.6 Paris agreement

Considering the Paris agreement, the objective is to derive the pathway at keeping the rise on temperature globally at a level much below 2^0C with all efforts geared at keeping it at about 1.5^0C (UNCC, 2015). Figure 2-5 depicts a compatibility with the 1.5^0C requirement on global temperature of the Paris agreement, but there still exists some emissions gaps at meeting the Paris agreement temperature level for the year 2030 (Figure 2-5). While the Paris agreement serves as a bridge between current global temperature policies and achieving neutrality on climate at the end of the century, it is composed of:

- Emissions reduction;
- Transparency;
- Adaptation;
- Damage and loss and

- Role of cities and local authorities

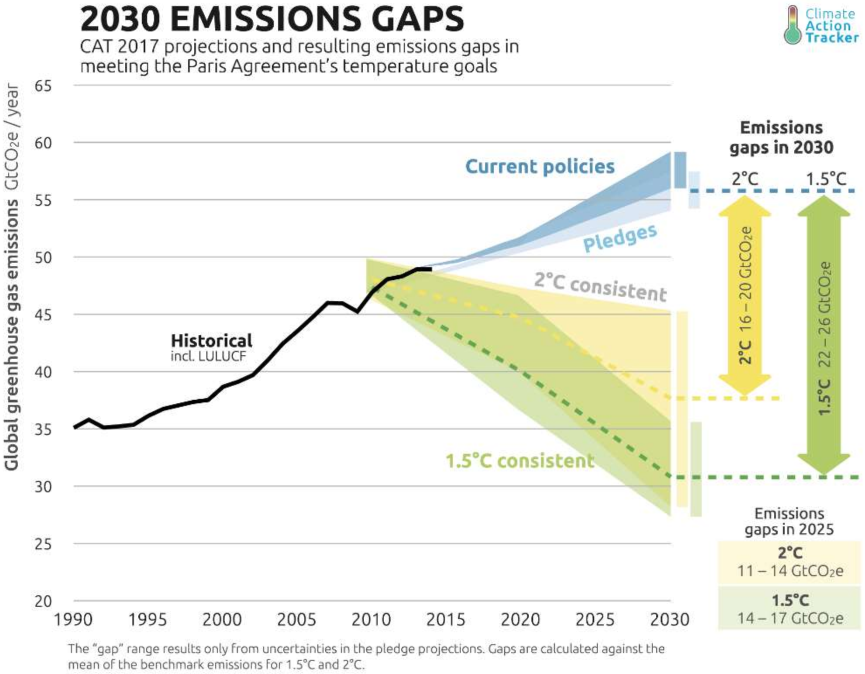


Figure 2-5 Emission gaps for the year 2030 (Climate Action Tracker, 2019)

2.1.7 Comparisons between 2020, 2030 and 2050 renewable energy policies

Considering the EU, the 2020 renewable energy production target base point for different countries varies country-wise. It is worth noting that, for Malta, a 10% increment is expected, while the expectation for Sweden is 49%, while a share of 10% in the transport sector is a requirement for all EU member countries (European commission, 2007).

By 2030, a mandatory target has been put in place for the attainment of 27% increment in energy efficiency, although, there has been an agreement for a review upwards to 30% on obtained level by year 2020 (European Commission, 2014a). In addition to the necessity of an unambiguous process that is flexible on the governing side, an inclusion of the end users must be considered (European Commission, 2014). However, the highlight of the 2050 policy, termed as the long term strategy is aimed at achieving a climate neutral Europe by year 2050 (European Commission, 2018).

Table 2-1 2020, 2030 and 2050 climate and energy framework targets at a glance (European Commission, 2007, 2014, 2018)

Targets	2020 climate and energy framework	2030 climate and energy framework	2050 climate and energy framework
GHG emissions	20% reduction from 1990 levels	≥ 40% reduction	80-95% reduction
EU energy share from renewables	20%	≥ 32%,	32.50%
Energy efficiency	20% improvement	27% increment with an upward review to 30% by year 2020.	Substantial increment

2.1.8 Emissions trading scheme & policy on EU/UK energy targets

It is worth noting that emissions from utilities in power and industry sectors on the large scale, in addition to those obtained from the aviation sector are covered under the emissions trading scheme (ETS), while the national emissions reduction targets (NERT), are accounted for by those in the housing, agriculture, waste and transport (HAWT) sectors, with the exclusion of emissions from the aviation sector (European Commission, 2007). Moreover, the EU's ETS is a strong tower of the European climate policy which sets a threshold for allowable maximum emissions for applicable sectors, thereby acting as a contributor to the GHG reduction targets set by the EU. ETS's 2020 target has a value of about 21% reduction from the 2005 level. Furthermore in the ETS's arrangement, applicable businesses can choose either to reduce their emissions or buy emissions from other companies in accordance to carbon prices, as shown in Figure 2-6, (Bagchi and Velten, 2012). Additionally, there exists NERT which adequately include those emissions that are not included in the ETS and having a major percentage of 45% of EU GHG emissions (European Commission, 2007). Moreover, there are annual targets that bind the EU in emissions reduction from NERT sectors in accordance to 2005 baseline effort sharing decisions (European Commission, 2007).

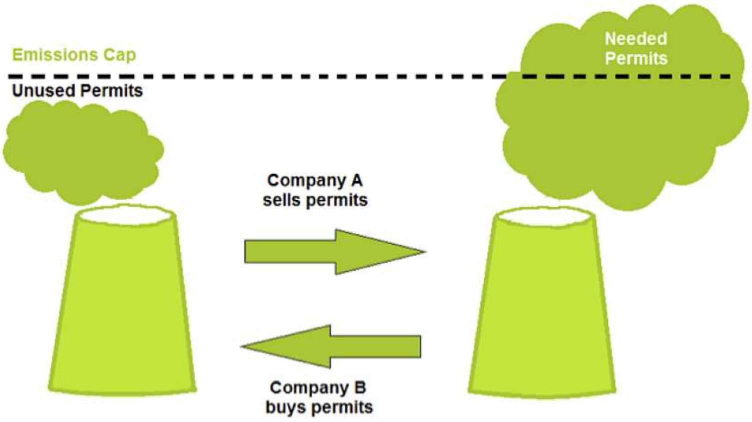


Figure 2-6 Emissions Trading Scheme (Energyryod, 2013)

2.1.9 Evolvement of renewable energy in the UK

United Kingdom's renewable energy is segregated into the sources for the production of electricity, heat and transport and reports shows that, contribution of renewable energy to eletricity generation in the United Kingdom commenced in the mid-1990s with its base on a little hydroelectric generating capacity. However, at the moment, wind power has exceeded that of hydroelectricity as UK's potential renewable energy resource. Of importance to note, is the increased interest in renewable energy usage for the purpose of emissions reduction, both in the UK and the EU. Additionally, incentives that were introduced for the achievements of the renewable energy targets both in the UK and the EU are commercial in nature. These include the Renewable Obligation Certificate scheme (ROCs) and Feed in tariffs (FITs), also included is the incentive that governs renewable heat, known as the Renewable Heat Incentive (RHI). However, in the year 2017, the percentage total of electricity, heat energy and transport energy that were generated from renewable sources were, 27.9%, 7.7% and 4.6% respectively (Digest of UK Energy Statistics (DUKES), 2018)

2.1.10 Issues surrounding lower levels of renewable energy share in the current global energy mix

Highlighted below are some challenges that could be contributory factors to the lower level of renewable energy share as regards the individual segments on the demand side of the energy supply chain networks:

- Lack of substantial level of awareness of energy efficiency, as regards those of renewable energy sources, climate change as well as technologies also culminates into issues regarding social acceptance in general implementation of renewable energy technologies *(Moula et al*, 2013).
- An appreciable number of consumers are indifferent about their sources of energy as long as it is accessible to them whenever it is needed, which also is a function of low level of awareness on efficiencies and benefits of embracing renewable energy sources and technologies and
- Set objectives/policies on energy frameworks (2020, 2030 and 2050), target industrial and commercial customers and less attention is directed towards impacts from the individual side of the supply chain, amongst other independent variables.

With the main goal of the energy policy in the UK being the complete (decarbonisation) of the economy through the utilization of sustainable energy material resources, increasing energy production efficiency and security as well as its supply to end users at a reduced and affordable cost, it is worth noting that, the achievement of these stated goals, will no doubt lead to a vibrant energy production from renewable sources.

2.2 Biomass classifications (based on sources)

Biomass, which is described as materials obtained from living or recently living organisms, has been considered in the course of this research work due to its abundant nature, a renewable energy source that is non-intermittent, carbon neutral, has a diverse nature of producing heat, electricity and fuel, serves as a source of revenue to its manufacturers and contributes to reduced garbage in landfills in areas where it is used, (MCFarland 2017). Generally, it is obtainable under the main categorizations shown:

- Agricultural remnants: Once commodity crops have been harvested by farmers, what is left on the field is termed as agricultural biomass. Remnants from alfafa, POME, EFB, nutshells, wheat, barley straw and corn stover are found in this group;

- Energy crops: These are a group of biomass that are a product of energy crops and are specifically grown for energy production. Hybrid poplar and trees from willow and switchgrass fall in this category;
- Forest residues: This is obtained from any biomass that remains after timber has been harvested, in essence, this group of biomass consist of bark, branches, leaves, needles, lignin as well as tall oil;
- Urban wood waste: Waste obtained from construction as well as debris from sites that are demolished fall under this group of biomass;
- Additionally, under waste biomass types, animal manure and sewage sludge are found and
- Algae/aquaculture biomass.

For a good number of reasons, biomass is a fascinating energy source, in essence, biomass sustainability and introduction in energy mix in power plants lead to a substantial reduction in GHGs emissions. It is worth noting that, when biomass is burnt, it releases almost the same amount of carbon dioxide as those obtained when fossil fuels are combusted, however, the CO_2 emissions from biomass are captured back by plants during its growth period, through the process of photosynthesis, hence, its carbon-neutral nature. Further, Iowa State University, (2011) stated that biomass usage in energy mix allows for reduction of dependence on imported oil as biofuel is the only renewable liquid transportation fuel and as such, leads to increased energy security in economies where it is used.

2.2.1 Sources of biomass in diverse/selected regions

Biomass resources are very diverse in nature, types of which include, but are not limited to: residual biomass, forest residues, agricultural residues, municipal waste, energy crops: crops for ethanol production, oilseeds, lignocellulosic crops, animal manure, landfills, waste water, wood waste, pulp sludge, grass straw, waste vegetable oil, animal fats and aquatic crops, with most of these biomass types, specific to some regions of the world (Pérez et al., 2017).

2.2.2 Comparison of biomass and coal fuel characteristics

2.2.2.1 Heating value

It is worth noting that, the heating value of biomass is considered as one of its most important characteristics. As it is a well-established fact that, the heating value constitutes the amount of energy contained in the fuel, and as such, the higher heating value (HHV) and the lower heating value (LHV) could be considered, with the HHV having priority for consideration over the LLV. However, the major difference between both is that, while the higher heating value (HHV) is the energy contained in the fuel in addition to that contained in the water vapour from exhaust gases, the lower heating value (LHV) does not consider water vapour from exhaust gases (Iowa State University, 2011).

Table 2-2 Higher Heating Values (HHV) for coal and biomass (Iowa State University, 2011)

Energy Material (Fuel)	Higher Heating Value (HHV) in MJ/kg
Coal	20-30
Combustible biomass feedstock	15-19
Agricultural residues	15-17
Most woody materials	18-19

2.2.2.2 Moisture content in biomass

The moisture content in biomass is a property that influences its combustion characteristics, indicating that material feedstocks with much water content burn less than those having less moisture content. However, if biomass material feedstock is too dry, it could lead to issues with dust and potentially lead to equipment contamination as well as explosion. In essence, the moisture content can be calculated on wet and dry basis (Iowa State University, 2011). It is worth noting that the moisture content of air-dried biomass range between 15—20%, while it is typically much less than that for oven dried biomass. With the moisture content contained in coal varying between 2—30%, on a practical note, the upper bound on moisture level for fuel combustion is 60%, although the value is much less, at about 40% for operation to take place in most commercialized equipment (Iowa State University, 2011).

2.2.2.3 Volatiles and mass yield of biomass against coal

During devolatilization, which is the removal of volatiles from solid substances, it has been observed that the mass fraction yield of biomass is higher than that which is obtained from coal (Koppejan and Baxter, 2013). During this process the yield from biomass is about 90-95% of its dry weight in comparison to coal which gives about 55-60% in value. It is worth noting that, devolatilization process which occurs at a fast rate is also dependent on temperature. Coal devolatilization yields char, having mostly carbon and potentially some ash components. Further, biomass, having a low particle density, aids its particles to oxidize at rates higher than those of coal with high moisture and size particles constituting to conversion issues for the fuel obtained during biomass co-firing process (Koppejan and Baxter, 2013).

2.3 Energy production from solid fuels

2.3.1 Coal-fired power plant

Coal can be described as the end product of organic residue spanning millions of years and solid in nature or as solar energy that has been stored for a long period of time. Like other fossil fuels, it takes coal several years of accumulation to be formed, however, the time taken to release its stored energy for electricity generation is negligible when compared with that necessary for its formation. With coal-fired power plants having conversion efficiencies of about 30-38% on higher heating value (HHV) basis as stated by Koppejan and Baxter (2013), biomass integration into a coal-fired power plant is modest and dependent on its moisture content with impact felt on the efficiency of the power plant. Furthermore, the emissions predicted from coal-fired power plants (Figure 2-7 and Figure 2-8) cause smog in the cities and have been linked to health issues surrounding respiration. Moreover, it is worthy to note that the percentage of atmospheric CO_2 emissions attributed to electricity generation from coal-fired power plants was 30% in the year 2018 (IEA, 2019), this emissions cause an increase in global warming and therefore affect climate change, thereby, necessitating an optimal pathway for its reduction.

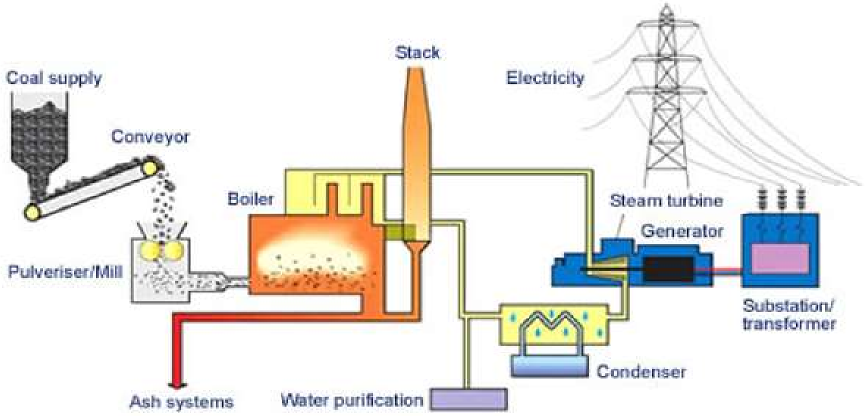


Figure 2-7 Design of a coal-fired power plant and conversion of coal into electricity (World Coal Association, 2019)

Figure 2-8 Coal-fired power plants (Strother, 2015)

2.3.2 Co-firing of coal and biomass

2.3.2.1 Overview on co-firing

Co-firing, also known as complimentary firing or co-combustion, is the burning together of two or more different types of materials (fuels), simultaneously in the same combustor for the provision of heat, (Figure 2-9). Biomass could be co-fired with coal in an existing coal-fired power plant (Figure 2-10) in order to reduce the environmental effects associated with coal combustion, (Koppejan and Baxter, 2013), in as much as landfill gas can be co-fired with natural gas. Both biomass and coal are solid fuels, and as such, co-firing them is feasible. However, there are drawbacks that are associated with biomass usage, which include, low efficiencies, having a higher cost than coal with increased levels of technical and financial risks during combustion (Koppejan and Baxter, 2013).

Furthermore, co-firing biomass in the form of straws, wood and sewage sludge with bituminous coal shows that the process results in the degradation of the efficiency of the boiler and some changes in its operational parameters (Belosevic, 2010). Additionally, it was reported that, when wood is co-fired with coal, there exists a reaction between alkali from wood and sulphur from coal, which invariably increases the fouling and slagging of the boiler, with the level of chlorine content in agricultural biomass aggravating corrosion of the boilers (Belosevic, 2010). In essence, there are basically three methods of technological set-up established for co-firing biomass in coal-fired power plants, the direct, indirect and parallel methods of co-firing. Direct co-firing entails co-firing not less than two fuels, simultaneously in the same boiler and it is the most common method due to the lower additional investment required on fixed asset and operational costs. It also has improved/high efficiencies obtained from a large scale coal-fired power plant as well as that reported on the combustible volatiles in biomass energy material resources (Belosevic, 2010). In the case of indirect co-firing method, it requires the solid fuels to be gasified and eventually combusted with gaseous fuel, while in parallel method of co-firing, fuels are combusted in different boilers, with the steam produced fed into same turbines. Additionally, it was observed that co-firing will impact costs, capital investments, logistics, plant efficiency as well as taxes applicable on the power plants (Eksioglu and Karimi, 2014).

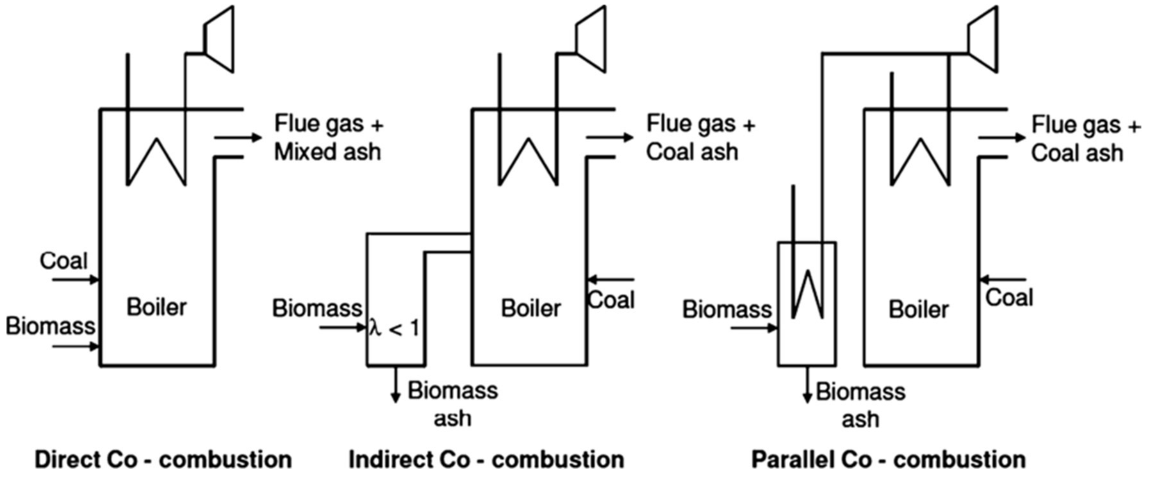


Figure 2-9 Co-firing of coal with biomass and waste in full-scale suspension-fired boilers (Johansen et al., 2012)

Operating costs incurred when biomass is co-fired with coal is higher than that of a coal-fired power plant, which occurs as a result of costs associated with biomass harvesting/collection, transportation, pre-processing and handling processes. Also, co-firing of biomass with coal is remarkably cheaper than combustion of biomass (Koppejan and Baxter, 2013). However, it is worth noting that wood-based biomass fuel is preferred because of its commercial nature and having less of fuel nitrogen.

Figure 2-10 Direct addition of woodchips on a coal conveyor at Wallerawang Power Station, Australia (Koppejan and Baxter, 2013)

Table 2-3 Comparison of biomass characteristics with coal (similarities and differences) (Pace University, 2000)

Properties (Physical & Chemical)	Biomass	Coal
Carbon content	Lower	Higher
Oxygen content	Higher	Lower
Silica & Potassium	Higher	Lower
Aluminium & Iron	Lower	Higher
Heating value	Lower	Higher
Moisture content	Higher	Lower
Density & Friability	Lower	Higher
Sulfur content	Lower	Higher
Chlorine content	Higher	Lower
Gasification property	Easier	More difficult
Reactivity & Ignition stability	Higher	Lower
Ash content	Lower, used as soil replenisher	Contains toxic metals & other trace contaminants
Vapour pressure & flammability	Lower	Higher

2.3.2.2 Differences in chemical composition of biomass and coal

It has been observed that, in a number of plants, combustion of biomass occurs with particles passing through a one-quarter inch, (6.35 mm) mesh, giving a particle size distribution that is less than 3 mm (Belosevic, 2010). It is worth noting that biomass particles that are larger than the size stated above or that have a higher bulk density, can accumulate at the bottom ash compartment of the boiler, where little or no conversion process takes place, except from drying (Baxter, 2005).

Furthermore, from a large number of co-firing tests performed on large-scale plants, with the use of different blends of biomass and coal in several combustion equipment, it was observed that biomass co-firing at low percentages combusts efficiently with a reduction in the amount of ash and slag formation within the combustion chamber. However, as biomass percentages increase, there is corresponding increase in ash and slag formation within the combustor. It is worth noting that fluidized bed systems combustor type have more flexibility than other combustor types in co-firing technologies with nitrogen oxides production not significantly impacted by co-firing (Ciolkosz, 2010).

Table 2-4 Table showing differences in chemical composition of Pennsylvanian's biomass and coal (Bain et al., 2003; Miller and Tillman, 2008)

Fuel	Carbon (%)	Hydrogen (%)	Oxygen (%)	Nitrogen (%)	Sulfur (%)	Silicon (%)	Potassium (%)	Calcium (%)
Anthracite coal	91-94	2-4	2-5	0.6-1.2	0.6-1.2	2-4	0.1-0.5	0.01-0.2
Bituminous coal	83-89	4-6	3-8	1.4-1.6	1.4-1.7	2-3	0.1-0.2	0.01-0.13
Wood, clean and dry	50	6.1	43	0.2	-	0.05	0.1	-
Switchgrass	48	5.5	43	0.2	-	1.4	0.4	-

2.3.2.3 Advantages of co-firing biomass with coal

When biomass is co-fired with coal, reduction is reported not only in net GHG (CO_2, CH_4) emissions, but also in some other types of pollutants such as sulphur oxides (SO_x) and nitrogen oxides (NO_x). But, there exists a proportionality between CO_2 reduction and the co-firing ratio, as the percentage of CO_2 emissions reduction obtained when biomass is co-fired with coal cannot exceed the original percentage of biomass, on a mass basis originally present in the co-firing combination. In essence, the lower ash content of most biomass fuel in comparison to coal result in the reduction in the solid residues that remain in the power plant after co-firing operation (Koppejan and Baxter, 2013).

In addition, biomass and coal energy material resources can be likened to a symbiotic relationship, where coal comes in handy as a substitute for the disparity encountered with biomass feedstock quality, while biomass, on the other hand breaches the gap on the environmental and social effects of coal power plants (Belosevic, 2010), with high similarity between lignite, brown coal and biomass (wood).

2.3.2.4 Review on experimental observations on co-firing biomass with coal

With a vast baseline on experimental observation of co-firing different biomass types with coal, knowledge of properties and biomass parameters required for optimal results have been improved upon. Belosevic (2010)) investigated the consequence of co-firing straw and pulverized coal, using two tests. Firstly, he used a burner with a thermal capacity of 2.5 MW_{th}. However, the straws used were cut and fed individually to the burner and had a thermal fraction basis which ranged between 0% and 100%.

Secondly, pelletized straws were pre-processed, milled together with coal and fed into a 250 MW_e boiler. Here, straws had a fraction between 0% and 20%. However, the results obtained from both tests showed reduction in nitrogen oxides and sulfur dioxide emissions. However, it was observed that weight percentage of biomass in the co-firing process, as long as it is not more than

20%, does not affect the stability of the fuel (Lu et al., 2008). Interestingly, biomass co-firing, with its inherent advantages of emissions reduction in power plants still have some factors that limit the co-combustion/co-firing process which is noticeable during direct and simultaneous feeding through existing coal mills. This depend on the mills performance, biomass drying capacity as well as the smoothness of utilized coal. In accordance with widespread opinion amongst researchers, the particle size should not exceed 1 mm. However, utilizing modern burners and technology gives some accepted values which could be as large as 100% < 8 mm and 30-40% < 1 mm (Belosevic, 2010).

2.3.2.5 Types of maintenance at thermal stations

Proper and timely maintenance of machinery at any power station is of utmost importance, as it not only prolongs the life span of the machinery, but also ensures their maximum production at high efficiency levels.

Some maintenance types that are carried out on machinery at power plants are described as follow:

- Preventive maintenance: This is recommended mostly on all equipment and invariably as a response to the likelihood of failure being proportional to the age or operating hours of equipment. However, there exists three key priorities that have been identified by power plant owners; safety, production level and efficiency and these priorities must have adequate plans in place, which must be adhered to.
- Predictive maintenance is same as condition-based maintenance, here, maintenance is performed only as needed, while, reactive maintenance's repair cost is higher due to premium that will be paid for immediate response.

With thermal efficiency of a steam-turbine power plant depending on input steam pressure to the turbine, input steam temperature to the turbine and the pressure in the condenser, the efficiency can be increased by increasing the steam pressure and temperature entering the turbine, while, decreasing the pressure of the condenser, steam re-heating between turbine stages and also, bleeding steam as it moves through the heating lines(Adegboyega and Odeyemi, 2011).

2.4 Energy supply chain networks

2.4.1 The energy supply chain networks

Energy, as a global necessity has the capability to performing work and with consideration given to heat and electrical types of energy, output derived from various operations performed on both types of energy can be used to work machines as well as power appliances, either industrially, commercially or domestically and for the provision of thermal heating, hot water and electricity to households and industries. As such, the processes involved in its generation through to its delivery require a high level of sustainability and continuous supply in a reduced cost and environmentally efficient ways. These, invariably, require thorough co-ordination of processes and operations in the design and planning of its supply chain networks.

Proper understanding of the different nodes of the ESC and identification of the major stakeholders can translate into making effective decisions as regards the procurement and management of energy for use, either at the industries or domestically (Energy Exchange, 2018). Moreover, it is worthy to note that, the ESC network for electricity generation consists of three main components:

(i) The energy commodity, which could be the generation of electricity at power plants or the production of natural gas;
(ii) Network services, which deals with energy transmission in high volumes from their sources of generation/production to the end users and
(iii) The distribution or supply, as well as energy metering to end users' premises.

Moreover, the fossil fuel ESC networks for electricity generation (Figure 2-11) consist of:

- generation points involving energy material resource and its costs;
- transformers used for the conversion of low voltage electricity to high voltage electricity which are necessary for efficient transportation;
- transmission lines with associated network costs;

- substation transformers that convert high voltage electricity to that of low voltage for distribution;
- distribution lines that also contribute to the network costs and
- Retail services that deal with the sales of energy products to customers (Energy Exchange, 2018).

However, the use of fossil fuels results in the emission of carbon dioxide (CO_2) as these non-renewable resources have limited availability that influences the security of energy supply in the long term. Ultimately, this calls for an immediate action directed at balancing the role of energy in technological, social, economic and environmental development towards a transition to lower-carbon energy sources (Ritchie and Roser, 2018).

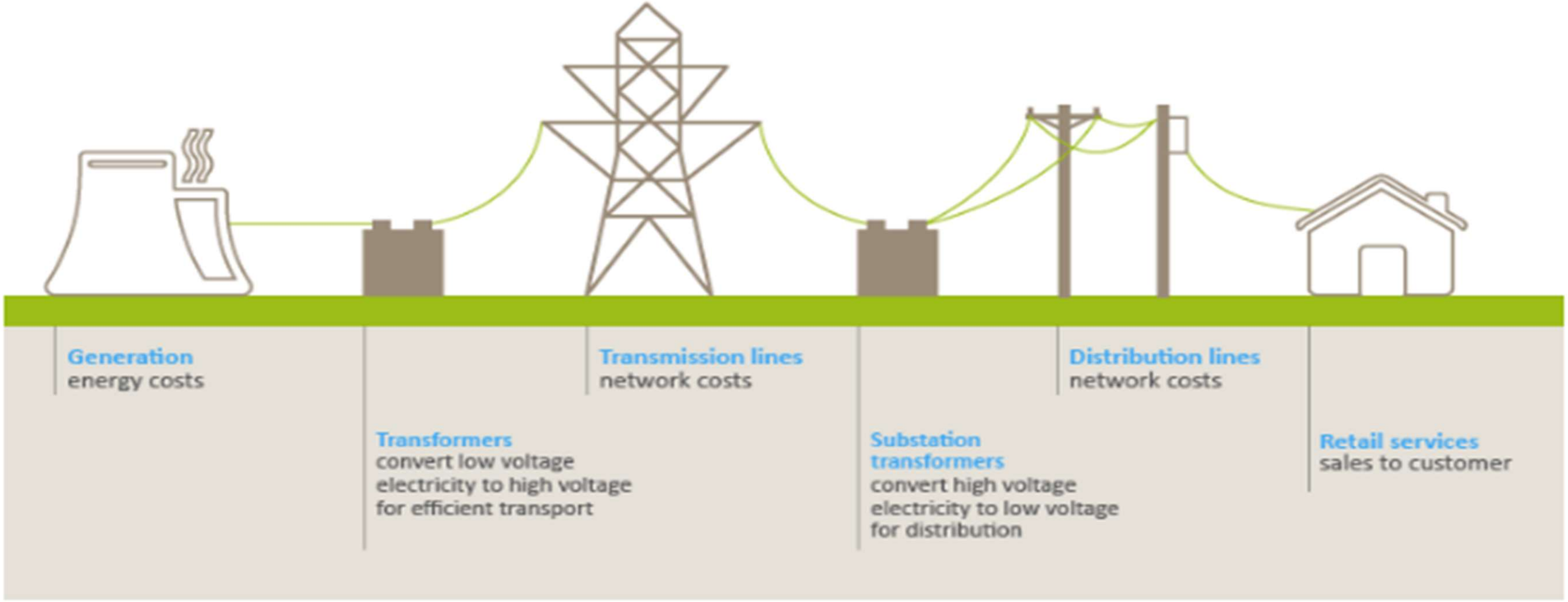


Figure 2-11 Energy supply chain network (QCA, 2019)

- Consequently, ESCs can broadly be divided into two major types in accordance with the input material resources that are responsible for energy generation; the non-renewable/fossil fuel-based and the renewable-based ESCs. In ESC networks, methods of sustainable and continuous energy generation, efficient production and delivery to end users at affordable prices in addition to simultaneous reduction in emissions keep getting better.

However, in 2018, the global share of coal demand in the energy mix rose by 0.7% or 40 Mtce (Mega tonnes of coal equivalent), considerably in excess of 10Gt partly due to its inexpensive nature (IEA, 2018a). But in contrast to the cheap attribute of coal, its generation comes with a significant amount of carbon emissions, in as much as CO_2 does not directly affect the ozone, unlike CFcs and HFCs, if its concentration is on the high side, then an indirect effect on the ozone layer in the stratosphere is reported. While an increase in CO_2 leads to a decline in the production of new ozone at areas closest to the lower stratosphere's surface and close to the equator, majorly during the spring season, an increament is reported in ozone levels at areas near the poles and close to the upper stratosphere. This occurs because of CO_2 preventing nitrogen from breaking down the ozone (Rose, 2018). Considering the large share of emissions attributed to CO_2, there also exists little amount of methane (CH_4) in atmospheric emissions, this little amount has large implications on global warming. From available records, global warming associated with methane is 34 times greater than CO_2 over a century period (UNCC, 2014). Moreover, nitrous oxide (N_2O) is released when fossils are combusted for electricity, heat generation and for transportation. Moreso, anthropogenic emissions with those from other sectors such as, transportation, industry and agriculture are still huge contributors to the level of GHG emissions reported. In essence, if adequate care is not taken at tackling the current global emissions issues, the cumulative effect, over a period of time could be catastrophic!

On a positive note, as against the 1990 base year, GHG emissions in the UK have reduced from a 41% level to 36%, a good one, with considerable efforts still ongoing to achieve a carbon-neutral economy, by 2050 (European Commission, 2018). In contrast, renewables integration in global energy mix, which could be a considerable solution to global GHG emissions reduction, but comes at a cost, higher than those obtained from fossil fuels, such as coal.

2.4.2 Fossil fuel-based energy supply chain networks

Key in the sources of fossil fuels for energy generation and production are: coal, oil and natural gas, with the natural gas-fired power plant burning natural gas to produce electricity (Figure 2-12). It is worth noting that, in the design of ESC networks, consideration is given to the establishment, installation and expansion of technologies that are carried out on the facilities as the need arises. Additionally, for the appropriate selection of machinery and equipment with their precision levels, experts' opinions are regarded.

Moreover, for an effective supply chain, adequate planning must be put in place in order for desired optimality to be achieved, with these decisions including both minor and major ones that need to be taken by all stakeholders involved in the processes. According to Pérez-Fortes *et al.* (2014), decision-making models that can accommodate multiple stakeholders and activities integrated in the supply chain should be developed. He further stated that this decision-making process across the activities in the supply chain fall under three types, strategic, tactical and operational decisions.

Awudu and Zhang (2012), further elaborated on the decision levels stated, with strategic decisions being long term decisions that could be revised after five or more years in accordance to the dictates of the business entity, and includes establishment of power plants. Tactical decisions are made on a medium-term basis which could span between six months and one year. In the making of the tactical decisions, inventory planning, logistical needs and distribution networks are usually taken into account. Furthermore, operational decisions are short term decisions that are made on a daily or weekly basis, while tactical decisions outlined above are achieved with proper operational planning (Miret *et al.*, 2016).

Figure 2-12 Natural gas-fired power plant (PowerGrid International, 2016)

2.4.3 Biomass supply chain networks

With components of wood and agricultural products making up about 46% of biomass energy and the most abundant type being the lignocellulosic biomass, (De Meyer *et al.*, 2014) studied on renewable and sustainable energy production with biomass occupying a significant share (between 40 and 50%) by 2050 in the renewable and alternative sources for the production of electricity, heat and transport fuels. Conversion technologies for forest biomass impact the economic, environmental and social aspect of the bioenergy production system (Gold and Seuring, 2011). Invariably, biomass energy recovery technologies can be classified into, direct combustion, gasification, pyrolysis, liquefaction, anaerobic (biogas production), aerobic decomposition, aerobic (ethanol production), and mechanical extraction (esterification), while the conversion processes can be thermochemical, bio-chemical or physicochemical (Toka and Lakovou, 2010). This has led to the consideration of these processes in the design and planning of its supply chain networks. The BSC network is the series of processes that biomass materials pass through from its points of supply (harvesting/collection) to its demand points (biorefineries/end users), as shown in Figure 2-13 and Figure 2-14. Moreover, in-depth understanding of the technologies available for biomass energy production is a pre-requisite for the strategic design of any BSC network (Toka and Lakovou, 2010). Additionally, Yue et al. (2016) reported a combination of life cycle assessment and multi-objective optimization to obtain a comprehensive life cycle optimization framework, which, asides from evaluating environmental impacts, also reported decisions that are better, both ecologically and economically. Further, Eksioglu and Hadi (2015) presented a nonlinear mixed integer programming showing the impact costs related to logistics, capital investments, efficiency of the power plant, credit obtained on tax as well as reductions in emissions, with the objective of profit maximization, which invariably resulted in reduction of overall cost of the ESC.

Moreover, the BSC is characterized by sources of variability, ranging from, weather uncertainty, low value on biomass feedstocks's bulk density, distribution of biomass suppliers, local logistics, transportation and distribution, contracts relating to supply and government policies (Cundiff et al.,1997; Gold and Seuring, 2011) which must be put into adequate consideration for an effective supply chain design and planning.

Toka and Lakovou (2010) also stated that, while reserves of fossil fuels, such as oil, gas and coal are the main sources of energy which are spread over only a small number of countries resulting in a non-stable energy supply that will be depleted in the foreseeable future, cost and complexity of logistics operations are two significant bottlenecks that hinder the increased utilization of biomass for energy production. Additionally, Rauch and Gronalt (2010), stated that, the demand for biomass for bioenergy production is always on the increase, which has led to a large increase in the procurement costs and distances for transportation for forest biomass, which is spread over large geographical locations and at varying distances from power plants, leading to the importance of using new and alternative ways to generate energy. These pathways are represented by processes which make up the different nodes of a BSC networks. According to Sharma et al. (2013), supply chains can be defined as the movement of materials from its source to the end users, with the proper management of supply chain taking into consideration all the activities involved from the supplier to the end-users. Additionally, the supplies must be on time, in the right quantity and must also satisfy the utmost reason for producing it, utilising least resources to achieve maximum outcome.Marvin et al. (2013), considered the BSC network as a combination of biomass producers, conversion facilities, and markets that are involved in biomass production, harvesting, storage, pre-treatment, processing, conversion, and its eventual transportation to the end users. Requirements of biomass feedstock at the biorefineries should be on a continuous, year-round, uniform, cost-efficient and reliable basis (Sharma et al., 2013).

Further, Allen *et al.* (1998) discussed the processes involved in the biomass supply chain networks, which include:

- Biomass harvesting or collection in the field or forest;
- Handling, which involves the movement of the biomass to a point of transportation;
- In field, intermediate site or storage at power stations. This is necessary as availability of biomass is seasonal, while its demand at the power station is on a continuous basis year round;
- Loading and transportation to the power station. The biomass is loaded unto transportation vehicles and moved to the power station for conversion into useful products and
- Processing, which may either be aimed at increasing its bulk density, as in the processing of coppice stems into wood chips or unitising the biomass. This is carried out at any stage in the supply chain, but must precede road transport. Additionally, It could also be carried out while harvesting to make the process cheaper.

Rentizelas et al. (2009b), (Figure 2-14) stated that, different biomass made use of customized equipment for their collection, handling and storage, thereby leading to complexity of the supply chain which also affects the investments and operational cost in the design of the supply chain. Bearing this in mind, adequate planning of the BSC is necessary in order to obtain a supply chain, having an overall reduced cost with a reduction in GHG/carbon emissions, an increase in efficiency and a continuous supply of feedstock all year round (Gold, 2011).

This has resulted to the general representation of the BSC, using the energy-state task network (E-STN) approach in the course of this research as one of the methods used for determining optimality in ESCs as shown in Figure 2-14 Generic biomass supply chain design (Rentizelas et al., 2009b). Moreover, it is worth mentioning that, Mafakheri and Nasiri (2014), considered the non-intermittent attributes of biomass as a renewable choice for energy production, while at the same time considered issues around the operational aspects apparent in the design and planning of its supply chain as biomass, being abundant in nature is obtained from varying sources.

Despite the extensive work that has been carried out in the design and planning of ESC networks, considering the advantages associated with biomass usage, from being carbon neutral, emissions reduction to those associated with energy security, a better alternative to disposals on landfills and creation of new jobs, (Thornley, 2006; Saidur *et al.*, 2011), there are still challenges associated with BSC networks, and these challenges need to be overcome

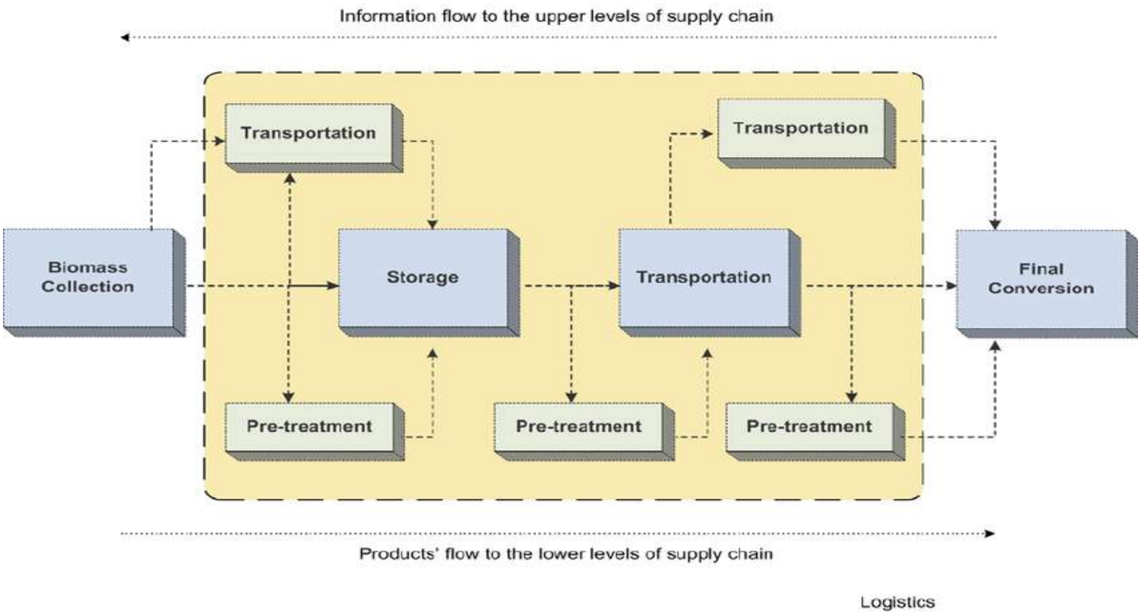


Figure 2-13 Biomass Supply Chain representation (Toka et al., 2010)

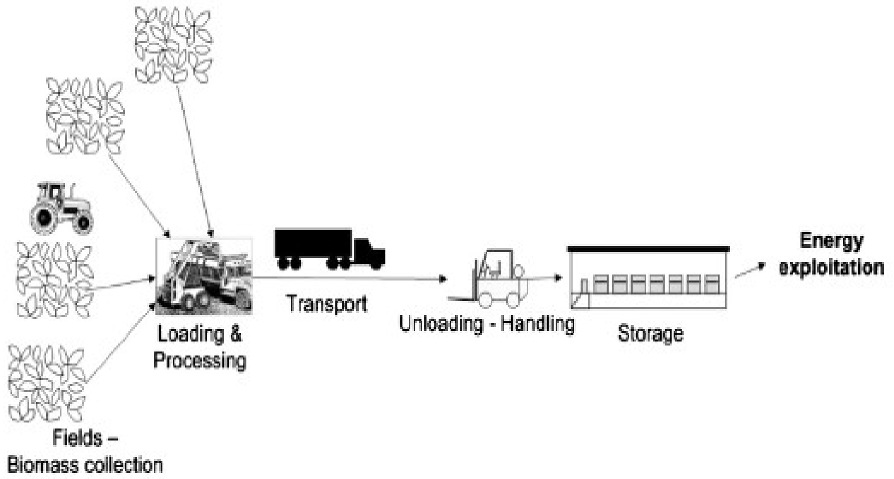


Figure 2-14 Generic biomass supply chain design (Rentizelas et al., 2009b)

2.4.3.1 Technology characteristics in biomass supply chain elements

With consideration given to the technology characteristics in BSC elements and and in addition to customized collection and handling equipment, BSC has a structure which is complicated in nature and is attributed to its heterogeneous nature (Iowa State University, 2011) in addition to reasons stated below, with markets for bio-based products, not well developed at the moment.

- Seasonal availability: Majority of agricultural, energy, and forest biomass resources are seasonal in nature. In essence, the seasonality feature of the biomass material feedstocks are due to some certain attributes, some of which are, crop harvesting period, weather conditions and field re-planting.
- Low energy density: Due to the low energy density nature of biomass material resources, more biomass is needed to provide the same amount of energy in comparison to an equivalent amount of energy obtained from hydrocarbon fuel. As a result, there is an increase in transportation and equipment handling, which also leads to the need for effective storage spaces.

2.4.3.2 Classification of available treatment (pre-processing) and conversion technologies for biomass materials

The technologies available for biomass processing and its energy production are very important in the study of the activities that take place in the BSC networks.

New generation of pre-treatment technologies are needed for techno-economic optimisation of upstream forest biomass value chain as pre-processing is carried out on biomass material resources in order to reduce its moisture content and increase its bulk density. However, the choices made at the points of biomass conversion to energy are dependent on a series of factors, majorly based on available biomass resource type as well as the associated quantity, legislation governing the applicable area and resources on the financial aspect of the supply chain (Saidur et al., 2011).

Atashbar et al. (2016) stated in their review that, there exists five types of pre-processing, which include, ensiling, drying, pelletization, torrefaction and pyrolysis. In essence, if biomass resources undergo any or a combination of the processes stated above, transportation to the biorefineries/power stations (where conversion takes place) will be smoother leading to a reduction in costs associated with logistics in the supply chain. Additionally, the conversion process is influenced by the type and quantity of biomass feedstock, end use requirements, environmental standards, economic conditions and other project specific factors.

Conversion of biomass into useful products is influenced by the type and quantity of biomass feedstock, the end use requirements, (either biofuel, biogas, biodiesel, etc), environmental standards, economic conditions and other project specific factors, with additional considerations given to processes involved in its mechanical conversion (Balat and Balat, 2009).

Gasification, pyrolysis and charcoal production are examples of thermochemical conversion process, whereby, biomass is converted into solid, liquid or gaseous fuel. During gasification, biomass is converted into combustible gas mixture by partial oxidation at high temperature in the range, 800-900 °C, while the conversion option based on biological processes is known as bio-chemical conversion. In consideration of bio-chemical conversion, some examples of processes carried out using this method are, alcohol production from biomass containing sugar, starch and/or celluloses, biogas production from crops or organic waste materials like, animal manure. However, liquid fuels (biodiesel) are gotten from physicochemical conversion process through physical (pressing) and chemical (transesterification) processing of dedicated energy crops, while the mechanical conversion process can either take the form of separation, extraction, drying and pelletizing. Finally, primary/intermediate products obtained through the forms of mechanical processes mentioned above include, lignin, biofuel, vegetable oils, organic acids and extracts with biofuel, heat, electricity, materials and oleo chemicals obtained as secondary products (Toka and Lakovou, 2010)

Table 2-5 Biomass conversion processes

Sources of Biomass (based on origin)	Process Type	Primary process	Primary products/ intermediates	Secondary Products
Wood and woody biomass	Thermochemical conversion	Gasification	Syngas, a mixture of H_2 +CO (e.g, Producer gas which is obtained from the gasification of coal, bio-syngas, which is obtained from the gasification of biomass)	Upgraded biogas (with an adjusted H_2/CO ratio),ethanol, plus C_3–C_4 alcohols, methanol, gasoline, formaldehyde, DME
Herbaceous and agricultural biomass (including agricultural waste and energy crops, pulp sludge, rapeseed, grass, crops:-either loose, shredded or baled		Pyrolysis	Solid fraction- char, biochar, Gas fraction- fuel gas, liquid fraction- pyrolysis oil/bio-oil.	Char/biochar, biopolymers
Aquatic biomass		Torrefaction	Torrefied biomass	

Sources of Biomass (based on origin)	Process Type	Primary process	Primary products/ intermediates	Secondary Products
Animal biomass wastes (animal manure, animal fats)		Hydrothermal liquefaction (HTL)	Solid, liquid and gas. The liquid fraction is called biocrude	Fuel upgrade to transportation fuels such as diesel, gasoline or jet fuels.
Contaminated biomass and industrial biomass wastes (including, MSW, sewage sludge, waste vegetable oil)		Combustion	Heat	Heat, Power (electricity), steam, mechanical energy.
	Biological conversion	Anaerobic digestion	Biogas (Methane)	Biomethane, Methanol, Olefins.
		Fermentation	Ethanol	Fuel, Ethylene, ETBE, ethylamines.
		Hydrolysis	Fermentable sugars	
	Chemical conversion	Supercritical conversion of biomass	Cellulose, hemicellulose, lignin	Fermentable sugars, biofuel (1st and 2nd generation), gasoline,

Sources of Biomass (based on origin)	Process Type	Primary process	Primary products/ intermediates	Secondary Products
		Transesterification/esterification with acid or base catalyst	Biodiesel	
		Solvent extraction	Cellulose, hemicellulose, lignin	ethanol, extractives, waxes
	Mechanical conversion	Extraction	Vegetable oils (castor oil, olive oil, waste cooking oil, rapeseed oil, sunflower oil), organic acids, extracts	Oleochemicals, biodiesel, green diesel (hydrocracking oil, fat feedstock)

(Tony Bridgewater, 2006; Bludowsky and Agar, 2009; Sadaka and Negi, 2009; Chen, 2014)

2.4.3.3 General waste biomass supply chains

The structure of the market for biomass and its associated supply chain has evolved dynamically on a global scale as biomass has been used mainly for thermal energy production in areas close to its production site. However, energy producers are procuring waste biomass from several producers in order to have an appreciable amount of the material that will justify the reasons to set up an energy production facility (Toka and Lakovou, 2010). As biomass is collected, it is either stored in field or transported to a storage area further away from the field and pre-treated in order to reduce its moisture content. The importance of biomass pre-treatment is to increase its bulk density before its final transportation to the biorefineries, where it is converted into useful products before its eventual distribution to end users.

2.4.3.4 Waste biomass supply chains planning models

In the planning of waste BSCs, issues around the following activities require appropriate consideration:

(i) Harvesting practices
(ii) Marketing channels
(iii) Logistics activities
(iv) Vertical co-ordination
(v) Risk management

Taking vertical co-ordination into consideration, there is a connection between assessment and lower levels, while the former gives objectives that are propagated to the latter, the lower levels provide detailed and relevant data which influence the modelling and the optimization of other levels when introduced (Miret *et al.*, 2016). Furthermore, Sharma *et al.* (2013) showed the factors considered when models are to be developed for a BSC (Figure 2-15).

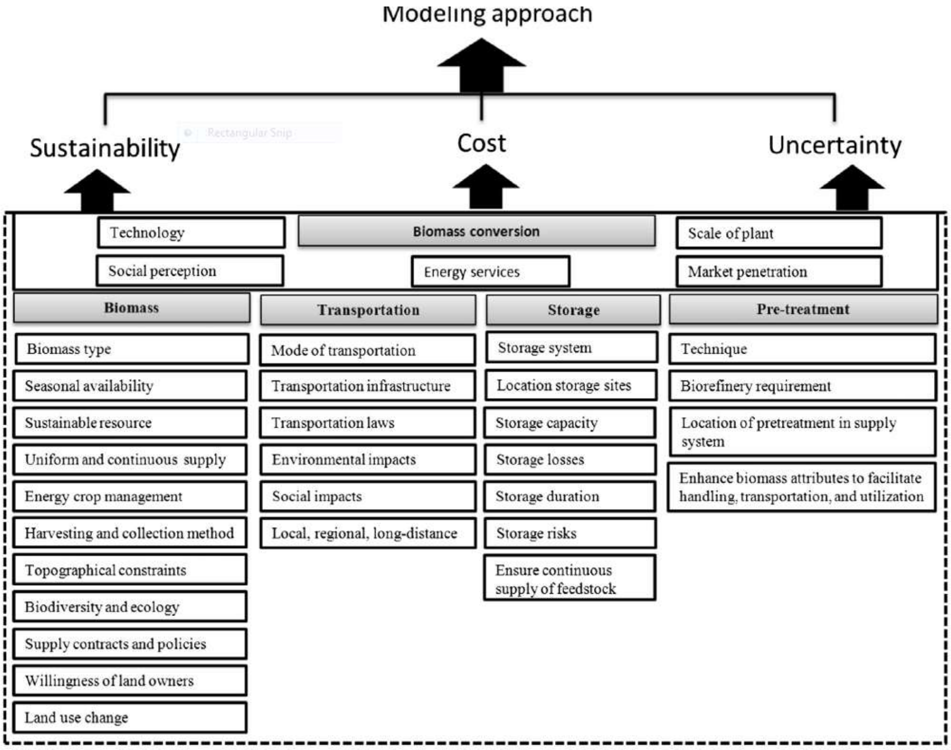


Figure 2-15 Factors considered for model development in a Biomass Supply Chain (Sharma et al., 2013)

2.4.4 Potential and existent locations for biorefineries/bioenergy plants

Decisions taken in the location of biorefineries/bioenergy plants are considered to be strategic in nature as it involves a large number of resources and combination of important group of industrial stakeholders. Serrano et al. (2015), mentioned that the location of the bio-refinery has an environmental influence which also involves the transportation and logistics activities in the supply chain. These locations can form part of the objective function that could be optimized in the general design and planning of the BSC networks. In spite of the large number of literature review articles on supply chain logistics, it's evident that those involving modelling issues still require improvement (Ba et al., 2015).

Table 2-6 A presentation of some of the world’s largest biomass power plants that are in operation (MW)

Biomass Power Plants (BPP)	Installed Capacity	Operating Status	Biomass materials utilized
Ironbridge power station	740 MW	Closed (November 2015)	Wood pellets
Alholmens Kraft, Finland	265 MW	Operational (since January, 2002)	Wood-based biofuels (forest residues), peat, coal (as a reserve fuel).
Polaniec, Poland	205 MW	Commercial operation (November, 2012)	Tree-farming and agricultural by-products.
Kymijarvi II, Finland	160 MW	Commercial operation (May, 2012)	Fuel recovered from solid, eg, dirty plastic, cardboard, paper and wood.
Vaasa Bio-gasification plant, Finland	140 MW	Operational (March, 2013)	Wood from forest residues.
Wisapower, Finland	140 MW	Operational (2004)	Primary fuel: black liquor
New Hope Power Partnership, US	140 MW	Operational (> 10 years)	Sugar cane fibre (bagasse), recycled urban wood.
Kaukaan Voima, Finland	125 MW	Inaugurated (May, 2010)	Wood and peat
Seinajoki, Finland	125 MW	Operational (since, 1990)	Main fuel: woodchips and peat. Backup fuel: coal

Source: (Alholmens, 2019); Technology, 2014).

Figure 2-16 The Ironbridge power plant at Severn Gorge, UK (Power stations of the UK, 2019)

The Ironbridge power plant at Seven Gorge in the UK shown in Figure 2-16 is the largest biomass power plant in the world having a capacity of 740 MW (**Table 2-6**). However, its installed capacity was 1000MW as it was previously a coal-fired power station, but, in 2013, two of the plant's units were converted to accommodate power generation from biomass resources (Power stations of the UK, 2019).

Moreover, Drax power station (Figure 2-17), was the largest coal-fired power plant in the UK and originally had a capacity of 3,960 MW, however, between 2013 and 2018, from the six units of the power plant, four were converted to 100% biomass fired plant, with the intention of converting the remaining two into gas-fired plant before 2025, a period considered for coal phase-out in Britain.

Figure 2-17 Drax biomass storage domes (Drax Power Station, 2017)

2.4.5 Some challenges encountered in the biomass supply chain networks

As earlier stated, the biomass supply chain is characterized by some major challenges which further complicate its structure and as such, necessitate its proper optimization. Challenges due to logistics as well as storage problems, which are due to its seasonal availability are some of those that largely affect the BSC. Here, quality degradation, material loss, danger of fire and formation of microbes that are dangerous to human health as well as sustainability issues which poses a challenge to the BSC.

According to McKendry (2002), the energy density of forest biomass is much lower than that of a large number of fossil fuels, resulting in the collection, handling, processing and transportation of large amount of forest biomass all through the service life of the conversion plant, which necessitate the need for optimal design of the supply chain

2.5 Modelling and optimisation of energy supply chains

2.5.1 Mathematical frameworks for supply chain systems

Mathematical models are sets of equations which describe real world phenomena, as such, mathematical frameworks for supply chain systems can generally be formulated to find optimal solutions to optimization problems. In order to formulate and solve mathematical models with the use of appropriate optimization software, basic concepts in optimization should be understood. In the course of this research, the General Algebraic Modelling System (GAMS) software has been used as it assists in the enhancement of visibility throughout the supply chain. Furthermore, some of the basic functions that need to be understood in the appropriate development of the mathematical frameworks include the following:

- Objective function: These are the actual functions to be optimized in a given system taking into consideration particular sets of decisions. Optimizing an objective function can either be a minimization or a maximization option.
- Sets: They are fundamental building blocks in any GAMS model, a representation of the entire system under consideration.The nodes of the BSC network can be considered as the sets in a model.
- Decision variables: They are the factors of the problem which are to be optimized and can be interchanged and controlled, examples of variables in a BSC network are costs, logistics, net present values and decision levels.
- Parameters: These are input data with fixed values, parameters in a given system cannot be changed.
- Constraints: They are the conditions that are considered and adopted in order to obtain a feasible solution, logics are represented here.
- Feasible solution: These are the group of decision variables that are embedded in the constraints and which also satisfy the constraints.
- Optimal solution: This is the best of all feasible solutions in a given system.

2.5.2 Mathematical modelling techniques for biomass supply chain design and analysis

In the classification of researches in the field of BSC networks, different criteria are considered among which the objective functions lie. Atashbar et al. (2016) stated in his review that, an objective function or optimization criterion can be described as the result of an effort to express a business goal in mathematical terms for it to be applied in decision analysis, operations research or optimization studies. It can also be described as the mathematical methods used to find the best solution (considering restrictions) among the many (or even infinite number) solutions to a given problem. Furthermore, there exists various methods of solutions that are applicable to BSC models, such as, mathematical programming solvers, heuristics, multi-criteria decision analysis (MCDA) methods, geographic information systems (GIS) and simulation methods (Atashbar et al., 2016). However, In order to determine sizes and locations of facilities, mixed integer linear programming (MILP) methods are developed and the suggested models are solved using commercial solvers.

Kim et al. (2011) developed a MILP for a supply chain that represented the raw materials, five different types of biomass in this case, that were used either in a pyrolysis plant for local energy production or in a conversion plant in order to obtain biodiesel and gasoline. Maximization of overall profit, which is the objective criterion, was achieved with consideration given to the location and sizes of the two plants. Additionally, the MILP model developed by Judd et al. (2010) was for the location of storages in-between small-scale storages on the site and bigger centralized storages. However, for non-linear programmes, which are characterized by computationally difficulties in their management, development of a generic algorithm gives an inceptive solution that could be upgraded with the use of a sequential quadratic programming (SQP) method.

However, in instances where solutions of mathematical models by commercial solvers are time consuming, heuristics are needed.In as much as their designs are developed to be faster than precise algorithms, there is no assurance on optimality. Yet, metaheuristics have been developed by a small number of researchers working on BSCs, here, the avoidance of confining varying processes to local optimum is of utmost importance (Atashbar et al., 2016) Further, in the work of (Ver*a et al*>, 2010) swarm-based algorithm, known as Binary Honey Bee Foraging (BHBF) was applied to a BSC problem with prunes remnants of Olive tree as the biomass material resource.

Elms and El-Halwagi, (2010) utilized the weighted sum aggregate method of multi-criteria decision analysis (MCDA), a mathematical tool that allows a good choice to be made amongst varying, often conflicting scenarios for the maximization of gains made from the sale of biofuels as well as incentives from reducing GHG emissions. With consideration given to the Analytic Hierarchy Process (AHP), Ma *et al.* (2005) used this tool in the selection of optimal sites for the positioning of anaerobic digesters on farms with consideration given to factors around economic, environmental and social effects.

For the Geographic Information System (GIS), which is a framework used in collecting, managing, analysing and storing data as regards geographical information. The work of Alam et al., (2009) utilized the GIS-based model for the optimization of forest biomass supply chain with the objective of minimizing total cost of the process in the supply chain. Moreover, for compounded systems having large numbers of connected activities, uncertainties in data and some level of stochasticity, where optimization models are not convenient for accurate predictions of their process solutions, simulation approaches and utilized. It is worth noting that for simulation methods, the considered system is modelled with simulation performed rapidly on a rather long time of its actual activities in order to compute varying performance criteria of the considered system.

2.5.3 Models overview for operation and maintenance planning of energy systems

In a combined heat and power (CHP) plant, both electricity and heat are generated in a single, homogenized plant, which can also be termed as a co-generation plant. Moreover, CHP, which is a technology is also a means of applying technologies which follows the process of recovering heat, which otherwise would have been wasted.

With some works in the open literature concentrating on the operational and maintenance planning, or a combination of both in cogeneration and other energy systems, Abdollahi et al. (2016) developed a mathematical model for the optimal design and operational planning of energy networks based on CHP generators. Zulkafli and Kopanos (2016) presented an optimization framework for the operational and maintenance planning of production and utility systems under unit performance degradation and alternative resource-constrained cleaning policies. (Silvente *et al.*, 2015) proposed a rolling horizon optimization framework for the simultaneous energy supply and demand planning in micro grids. Bischi *et al.*, (2014) presented a planning model for combined cooling, heat and power systems while Alipour et al. (2014) studied the short-term scheduling of CHP units under demand response programs. Hirvonen *et al.* (2014) proposed local sharing of cogeneration energy through individually prioritized controls for increased on-site energy utilization, while Wakui et al. (2014) presented a mathematical programming model for cogeneration-based residential energy supply networks. Kopanos et al. (2013) developed mathematical models for the energy production planning of a network of residential CHP units, considering different network structures and analyzing alternative objective functions. Morales et al. (2013) and Ostrowski et al. (2012) presented mathematical models for the unit commitment problem, which could be considered relevant to the planning of cogeneration plants. Cristóbal *et al.* (2012) proposed a multi-objective optimization framework for the planning of coal-fired electricity production plants considering CO_2 capture and preventive maintenance. Li and Nilkitsaranont (2009) presented a multi-objective optimization model for the modeling of the CO_2 capture process based on of coal-fired electricity production plant. Alardhi and Labib (2008) proposed a mathematical programming model for the preventive maintenance scheduling of multi-cogeneration plants. Detailed information on the maintenance planning industry along with insights to optimization and iteration methods to generate suitable maintenance plans can be found in Duffuaa et al. (1999). Furthermore, Hanak et al. (2015), in a bid to suggest ways by which the power sector can be decarbonized, identified and evaluated integration of calcium looping to the power generation system, which resulted in a forecasted efficiency penalty of 2.6-

7.9% points and 9.1-11.4% points for coal-fired power plants and combined-cycle power plants respectively.

It is observed that typically energy production and maintenance are considered individually or optimized sequentially, resulting in a need for optimization approaches that integrate these two major decision functions. For this reason and in the course of this research, a new optimization approach for the simultaneous planning of energy production and maintenance in cogeneration plants is developed to bridge the first research gap. In essence, the proposed optimization model is applied to an annual planning problem in the largest cogeneration plant of Kazakhstan (The KUS), to highlight the significant improvements achieved in the resource and energy efficiency of the plant along with major total cost reductions.

2.5.4 Various optimisation-based approaches for the design and planning of energy supply chain networks

Optimization, which is a vital support tool is concerned with the maximization or minimization of an objective or several objectives, which allows the best solution to be obtained systematically, however, constraints must be satisfied by a solution to a problem. Furthermore, optimization models built from general modelling representation developed with the incorporation of single or multiple objective functions is suitable for use in simulation studies before certain decisions are taken, while the insights gained through the optimization process can identify potential changes that can improve the ESC networks.

2.5.5 Optimization models for the design and planning of energy supply chain networks

2.5.5.1 Design models

In design optimization models, values of specific design variables are determined, moreover, optimization, which can either be a minimization or a maximization function is performed on the objective functions, while performance criteria and other associated constraints must be satisfied (Hermann et at., 2003)

Stated below are some works of researchers that center around this type of model.

(i) Miret et al. (2016) concentrated on multi-objective optimization method which considered, economic, environmental and social sustainability dimensions to optimally design a BSC network in order to ensure its viability for a long period of time.

(ii) Ekşioğlu et al. (2009) looked at issues related to logistics in the supply of biomass to a biorefinery, in additon, a mathematical model was presented for the effective design of the BSC and consideration was given to the logistics process in a biorefinery.

(iii) To further contribute to the design and planning of ESC networks. In corroboration of the work of Ekşioğlu et al. (2009) which considered logistics issues of a BSC, Rentizelas et al. (2009a) stated that a voluminous portion of costs incurred in generating energy with bioenergy resources lie with those associated with its logistics. In view of the aforementioned statement, their model also placed emphasis on biomass storage and their solution contributed to biomass storage issues, with analysis performed on biomass storage methods (Rentizelas et al., 2009b).

(iv) Rauch and Gronalt (2010) utilized the MILP method to choose appropriate structural arrangement and terminals for the location of bioenergy plants in order to re-design the biofuel supply chain. However, in a quest to show the viability of biomass utilization for electricity generation, Simonyan and Fasina (2013) researched into the available biomass resources in Nigeria with its associated conversion technologies and with discussions centered around its advantages and issues encountered in the supply chain.

2.5.5.2 Planning models

As optimization models are developed to attain a goal, while simultenously considering variables and constraints, planning models, which are examples of optimization models are most often applied when a large number of alternatives, which bring about remarkably different outcomes are considered (Arbow, 2017). Moreover, optimization-planning models are important and could be operational (short term), tactical (medium term) and strategic (long term). Stated below are some of the planning models that have been reported in literature.

(i) Zhu et al. (2011) developed a mixed-integer energy model used for energy systems planning in the city of Beijing. In their model, interval-parameter programming, mixed integer linear programming and full-infinite techniques were developed to achieve capacity expansion planning in energy systems in the city of Beijing, and were able to accommodate expansions in both supply and demand of energy resources. Furthermore, their model allowed trade-offs amongst cost, efficiency, emissions reduction as well as energy security.

(ii) Furthermore, (Kopanos et al. (2013) proposed, modelled and optimized a micro-generation energy supply chain network, based on domestic-scale micro-generation via an equally micro-combined heat and power systems, their model permitted exchange of electrical energy between residentials connected to the domestic grid and an eventual power exchange with the power grid, the objective function of the model was to obtain optimality in the operational planning of the ESC networks through total cost minimization, while fully satisfying heat demand on the connected micro grids.

(iii) Haghighi et al. (2016) proposed a combination of biomass supply chain and DEA networks used for the evaluation of sustainability in supply chains.

(iv) Castro et al. (2008) investigated optimization with process scheduling as well as heat and power management.

2.5.5.3 A combination of design and planning models

(i) Kopanos et al. (2018) presented an efficient optimization model that was used for the simultaneous energy production and maintenance planning of combined heat and power plants. In order to demonstrate the efficacy of the model, the mathematical formulation was applied to the largest coal-fired cogeneration plant in Kazakhstan. And as such, the optimization goal of minimizing the annual cost of the cogeneration plant was achieved. The solved model returned a 21% reduction in the overall annual cost of the plant.

(ii) Moreover, Zulkafli & Kopanos (2018) proposed a spatial optimization structure using the modified state-task network approach to investigate the trade-offs between emissions and costs in material and energy supply chain networks.

(iii) Laínez and Puigjaner (2012) considered supply chain optimization in chemical industry, a conduct into in-depth review of the newest conceptualization frameworks of supply chain was carried out using ideologies for general model representation as regards varying connection levels at varying times and space periods.

(iv) Miguel Laınez *et al.* (2009) researched on the flexible design-planning of supply chain networks. In their work, supply chain (SC) was described as a collective network, with an appreciable number of business establishments working together to obtain un-processed materials, convert these un-processed materials into specific final products as well as the delivery of the final products to retailers. In addition to the processes mentioned above, the presented SC has characteristics of materials flow in an onward direction and information flow in a reverse direction. He further gave a combination of processes in a SC, which entails, un-processed/raw materials, information and monetary flows to deliver products, goods and services to consumers.

(v) Moreover, Zulkafli and Kopanos (2016) also considered simultaneous operational and maintenance planning, with the processes based on utility and production systems'

(vi) Further, Laínez and Puigjaner (2012) reviewed modelling and optimization in chemical process sector, in their work, investigation on the different processes that make up the supply chain networks was performed. Their approach deviated from the long-established approach which focused majorly on operations in the SC to a much more homogeneous idea, incorporating decisions from areas such as, up to date product development, large finance, in addition to those that deal with the environment.

2.5.5.4 Economic models

(i) Additional study was conducted by Balat and Balat (2009) to examine the economic, environmental and political effects of hydrogen production from biomass.

(ii) Moreover, Balaman & Selim (2015) developed a fuzzy-based multi objective decision making model for simultaneous optimization of varying economic based objectives. Its feasibility was tested using computational experiments on parameters obtained from biomass to ESC that existed in real world. Further, effects of different operating conditions and energy crops utilization were investigated with the use of scenario analyses.

(iii) Additionally, in accordance to the multi-objective optimization approach, Mirkouei et al. (2017) focused on modelling and optimizing techno-economic variables in the components that constitute the upstream component of the biomass to biofuel supply chain.

With most work having the perspectives of either designing or planning of energy supply chain networks individually or sequentially, there are no identified works that simultaneously deal with energy production and maintenance planning approach in a large coal fired combined heat and power plant, hence, same has been addressed in the course of this work.

2.6 Research methods

There exists various types of research methods (Figure 2-18) used in the collation of research data in order to complete in-depth analysis on subjects under study. In essence, these methods are grouped under the qualitative or the quantitative types of research. Interviews, observations, focus groups, document analysis and life stories can be categorized under qualitative techniques, while, questionnaires/surveys, document screening, experiments and observation are all examples of quantitative techniques

- Experiments: In the conduct of experiments, participants are requested to undergo different tests in order to ascertain their cognitive abilities, with comparisons drawn from results obtained from different groups. The aim of conducting experiments is based on determining the links between individual or groups' performances and other factors (Alzheimer Europe, 2009). Moreover, experiments may take the form of hypothesis testing in laboratories, tests carried out on relationships between cause and effect or through quasi based/natural experiments (University of Newcastle Library guides, 2019).
- Surveys or questionnaires: In surveys, information is obtained from a reasonable large number of individuals through questionnaires or other methods, such as interviews or via telephone. Moreover, the questions asked in surveys are same
- Interviews, on the other hand can be in form of structured, semi-structured or unstructured types and take place between the participant and the researcher, however, in some cases, the interviewer may not necessarily be the researcher
- Observations: The observational type of research methods considers the frequency of occurrence of a specific data or the translations of data obtained during the process into codes in order to represent it as numbers (University of Newcastle Library guides, 2019).
- Delphi method: The Delphi method of research was developed in the United States around 1950s and 1960s around the military realm. Its aim is for the

measurement of diversity as well as consensus which exist amongst participants on a specific subject (Alzheimer Europe, 2009).

- Case studies: This research method deals with in-depth study of a particular person or a small group as most often, observations and interviews are used via the consultation of personal or records held by the public as well as other people. The focus of case studies is very narrow and unique to the case studied.
- Participant and non-participant observation: In participant observation studies, the researcher conducting the studies is part of the group being observed. Here, the researcher must fit into the group to be observed, gain their trust and also be un-biased in the conduct of the work, while in non-participant observation, the researcher is not part of the group.
- Observational trials: In the conduct of health issues in a substantial number of people, this research method is used, with the approach being longitudinal. In longitudinal approach, attitudes of people, who share a common characteristic within a specified, long period of time is examined, these people are also referred to as a cohort. In some other cases, a retroactive approach can be used.

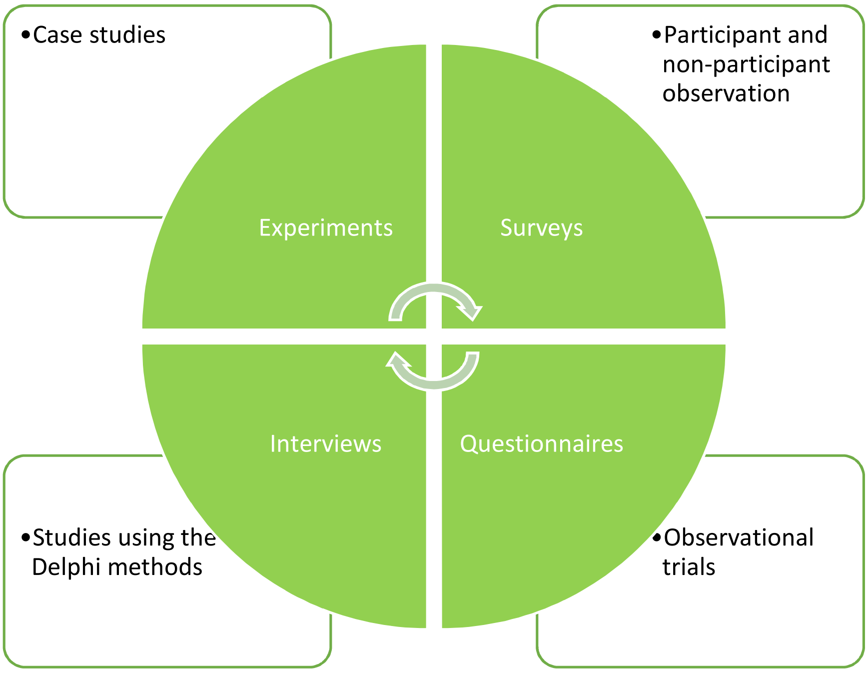


Figure 2-18 Types of research methods

2.7 Sampling methods

In general, sampling methods can be either probability or non-probability samples (Figure 2-19). Probability samples are those whose population segment have a non-zero chance of being chosen for the sample, while it is not so for the non-probability samples.

In essence, a population segment may never be chosen when the non-probability samples method is used. However, the use of this method is characterized with advantages of convenience and cost.

Yet, the non-probability sampling method does not give allowance on the extent to which sample statistics are likely to be different from population parameters, as this is only allowed if probability sampling method is used (Stat Trek, 2019).

Furthermore, two main types of non-probability sampling methods are: voluntary and convenience sampling, while probability sampling methods can either be one or a combination those stated below:

- Simple random sampling / Lottery;
- Stratified sampling;
- Cluster sampling;
- Multi stage sampling and
- Systematic random sampling

Balta-Ozkan and Gallo (2018) investigated the impact of differing energy behaviours and perspectives across varying European geographical factors. In their study, Eurobarometer survey data was used in the analysis of energy behaviours that are influenced by varieties of rural and urban surroundings as regards European geographical regions under consideration. Further, the acceptance level of the Finish on renewable energy technology (RET) was studied by Maula et al. (2014), In their work, multiple choice questionnaires with questions covering segments on renewable energy background information, RETs' awareness and disposition towards investment in RETs were distributed to 50 recipients.

Moreover, a critical analysis into already performed study on RETs' acceptance was conducted by Devine-Wright (2008) with an insight into combination of circumstantial, conceptual and personal factors that determine public acceptance. Additionally, a couple of studies re-iterate the fact that, in a particular concept, the measurement of social acceptance on technologies can be achieved with the aid of several indicators (Bagozzi et al., 1992; Devine-Wright, 2008). Furthermore, there was an analysis conducted on a survey that was based on regional level by Somerset County Council in 2004 in the UK. In their findings, the council concluded that in addition to awareness and renewable energy opposition, higher levels on both factors were reported by respondents that are in the older age groups (65+). But, analysis of survey results conducted by (Urban and Ščasný, 2012) indicated that both factors mentioned above, i.e, awareness and opposition to RETs were noticeable among both the younger generation (ages 16-24) as well as the older generation (65+), while there was support reported from the middle age groups, (ages 35-44 and 55-64).

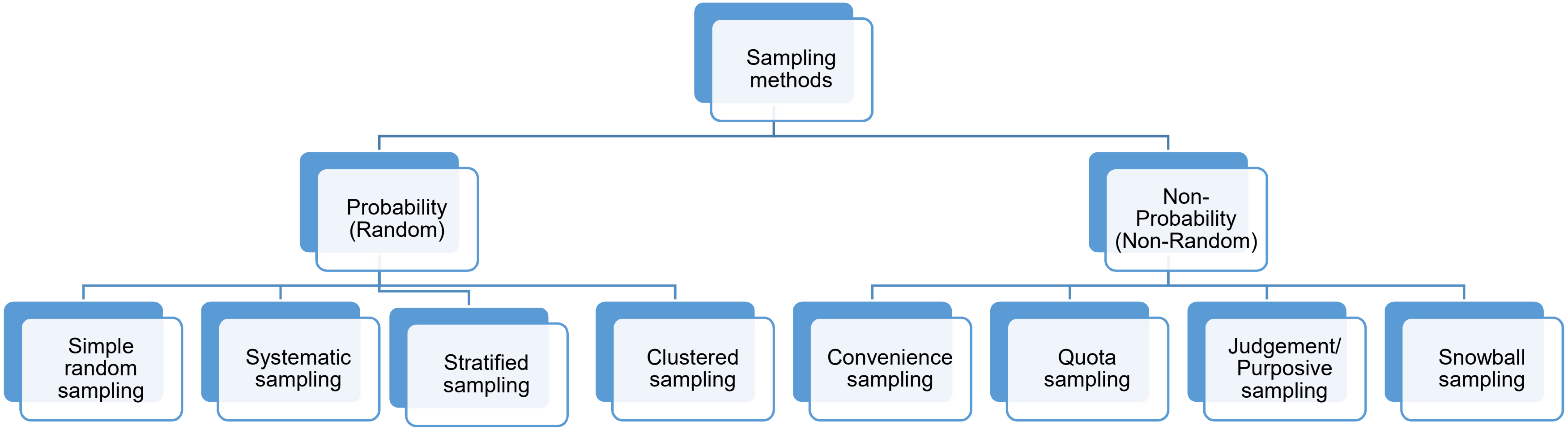


Figure 2-19: Categorization of sampling methods (HealthKnowledge, 2009)

With a large base of study of individual consumers on the domestic side of the energy supply chain networks, however, it is worth noting that, government's policies and legislations on frameworks that address the consumers on energy networks is not a robust one.

As a result of this development, the third objective of this research work focuses on the use of mixed research type to study and analyse individual consumers' responses on energy generation and usage. In addition, the analysis and use of these responses in the proposition of strategies that will lead to improvement in renewable energy embracement in the UK energy mix, with these proposed strategies being the new learning that has emanated from the conduct of this survey.

3 METHODOLOGY

3.1 Description on theory and methods of the Karaganda Utility System

The first case study considered in the course of this research looks into Kazakhstan, which is a low-populated vast country that is the major financial player in Central Asia due to its huge reserves in major natural and mineral resources, such as coal, oil and gas, uranium, lead, chromium, zinc, copper, manganese, iron and gold. From 2000 to present, the country has experienced a remarkable economic growth and an increase in population from 15 to over 18 million (Trading Economics, 2017; Ministry of National Economy of the Republic of Kazakhstan Committee, 2017), resulting in a significant increase in energy demand. The electricity demand in Kazakhstan has increased from 55 billion kWh in 2000 to 90.8 billion kWh in 2015, and it is estimated to reach 104.1 billion kWh in 2022 (Kazakhstan Electricity Grid Operating Company, 2015; KAZENERGY, 2015). Heat demand is also large in Kazakhstan due to its sharply continental climate with extremely cold large winter periods. In addition, the energy intensity of Kazakhstan's economy is twice as high as the average level of OECD countries, and 12% higher than that of Russia. Kazakhstan adopted the “Energy Efficiency 2020” program with the aim to reduce its energy intensity by 50% in 2050 (reference year is 2008).

Kazakhstan was ranked first in the world from the standpoint of intensity of carbon dioxide emissions per unit of GDP by International Energy Agency (2014), and has set an ambitious target of 15-25% economy wide reduction in GHG gas emissions by 2030 (reference year is 1990) within the framework of the Intended Nationally Determined Contribution under United Nations Climate Change Conference, COP21 (*European Union External Action*, 2015). The international commitment is primarily reinforced by the “Concept for Transition of the Republic of Kazakhstan to Green Economy” addressing the efficient management of the resources, developing a new national infrastructure and renovating the existing infrastructure. Kazakhstan Strategy 2050 aims at emissions reduction to 40% by 2050 through higher penetration of renewables and improvements in resource and energy efficiency (Green Economy, 2013). However, the current fossil fuel-friendly regulatory framework, and huge availability of conventional resources result in low-cost energy for both residential and industrial uses, making low-carbon solutions unattractive economically (Karatayev et al. 2016a; Karatayev *et al.* 2016b). There is a clear need for strategic energy system planning incorporating environmental and economic trade-offs (Zeng *et al.*, 2011). This should involve improvements in resource and energy efficiency in energy consuming and generation sectors, while acquiring economic benefits (Sarbassov *et al.*, 2013). Efficient management strategies both in the investment-strategic and operational level in the power sector are also essential (MacGregor, 2017).

In Kazakhstan in 2015, coal-fired Combined Heat and Power (CHP) plants account for 81.6% of the total installed capacity for energy generation, followed by 10.2% of hydro, and 8.0% of gas (KAZENERGY, 2015). There are 111 CHP plants with total installed capacity of 21.3 GW and available power of 17.5 GW (McPherson et al., 2017). Most CHP plants are located in Pavlodar, Karaganda and East Kazakhstan due to a well-developed industrial infrastructure and associated steady electricity demand and high heat demand. The wide deployment of CHP plants in the power system of Kazakhstan was dictated by the Soviet central planning, as a convenient means for utilizing low-grade heat for district heating due to extremely cold climate and abundance of coal reserves. It is clear that cogeneration plants play a vital role in satisfying the energy demand in Kazakhstan, support the growth of the economy, and contribute to the well-being of the population especially during the long winter periods. For this reason, this study focuses on the management of the energy production and maintenance in such energy plants.

3.2 Proposed optimization framework for Karaganda Utility System

The framework for the optimization method that was applied on the largest coal fired combined heat and power plant in Kazakhstan, otherwise known as the KUS, focuses on the simultaneous energy production and maintenance planning of the largest coal-fired combined heat and power plant in Kazakhstan, which is owned by KUS LLP and is located in Karaganda. The KUS CHP plant started its operations in 1976. Figure 3-1 displays a simplified schematic representation of the layout of the KUS CHP plant, which is a typical CHP plant layout for other CHP plants in Kazakhstan as well as in other post-Soviet states. As it can be seen in the figure, the KUS CHP plant consists of eight boilers (B1-B8), six multi-stage steam turbines (T1-T6), and two Reduction Cooling Units (RCUs). The network of boilers generate steam that pass through a major steam pipeline and enters the network of turbines for electricity generation. The outlet heat flow of each turbine is used to satisfy the heat demand of the two heat networks connected to the CHP plant. Reduction cooling units (RCUs) could be used to overheat water up to 120°C when ambient temperature is below -10°C as it supplies heat directly to the heat networks from the main steam pipeline, bypassing the turbines. Turbines T1-T3 are connected to the first heat network, and turbines T4-T6 are connected to the second heat network. The turbines usually operate under a 130 atm steam pressure and 555°C temperature mode, and their efficiencies are subject to the ambient temperature. The steam turbines of the plant offer the flexibility to extract steam from different stages of the turbine. This means that the heat and power generation are not strongly connected by a constant power-to-heat ratio as in the case of back-pressure steam turbines. Instead, the turbines of the plant can operate within a feasible operating region. The produced electrical power and heat from each turbine depend on the steam inlet. The cross-linked steam pipeline structure adds another layer of flexibility to the system, since it reduces the dependence on individual boiler operations, maintenance and unexpected events. The KUS CHP plant is connected to the national electricity grid, from where it receives demands for electricity. Annual maintenance tasks for boiler and turbine units are predefined and follow a conservative policy to avoid potential damage of the equipment. Energy production planning is performed empirically by considering the known maintenance plan. In addition, significant material and energy resource consumption (i.e., coal, electricity and heat) is required during the startup of boiler and turbine units. Currently, no proper optimization takes place during the generation of energy production and maintenance plans.

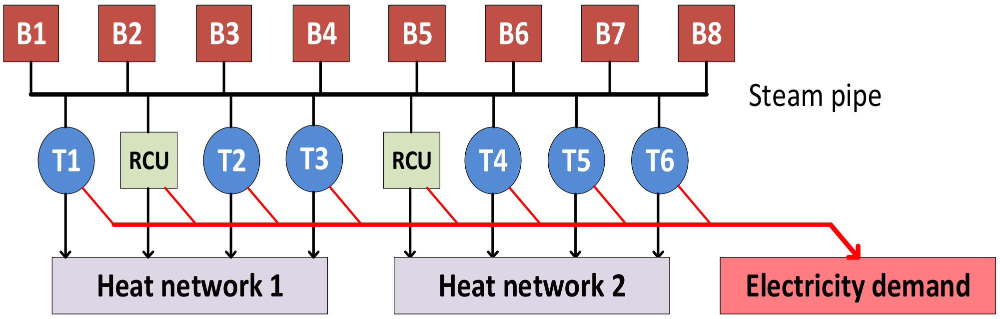


Figure 3-1 KUS CHP plant layout (red boxes: boilers, blue circles: turbines, RCU: reduction cooling unit).

To improve the current industrial policy and demonstrate the opportunities for overall energy efficiency in the CHP plant, an optimization framework is developed for the simultaneous planning of energy production and maintenance for the KUS CHP plant, described above. It is necessary to provide a detailed problem description before presenting the proposed optimization model. The problem under study can be formally defined in terms of the following items:

- A time horizon T that is divided into a number of equal-size time periods, $t \in T$.
- A set of units $i \epsilon I$ that consists of a number of boilers, $i \epsilon I^B$, and turbines, $i \epsilon I^T$ with given efficiencies $\eta_{(i,t)}$.
- A set of heat networks $j \epsilon J$ (connected to the CHP plant) that each one has a dedicated RCU with given efficiency η_j^{RCU}.
- A given demand profile for electricity (ζ_t^{el}) and given heat demand profiles for each heat network ($\zeta_{(j,t)}^{hea}$).
- Given factors for internal electricity and heat requirements for the CHP plant (β_t^E and β_t^H, respectively).
- Given minimum runtimes (ω_i) and idle times (ψ_i), for boiler and turbine units.
- Boiler units are characterized by maximum (minimum) heat generation levels $\theta_{(i,t)}^{max}$ ($\theta_{(i,t)}^{min}$) and heat losses factors $loss_i$.

- Turbine units are characterized by maximum (minimum) electricity generation levels $\varepsilon_{(i,t)}^{max}$ ($\varepsilon_{(i,t)}^{min}$) within desired operating regions, and maximum outlet heat flows $\theta_{(i,t)}^{Tmax}$.
- Given earliest and latest starting times (τ_i^{min} and τ_i^{max}), with durations (ν_i) and costs ($\kappa_{(i,t)}$), for the maintenance tasks of boiler and turbine units.
- Given costs for startup ($\alpha_{(i,t)}$), shutdown ($\varphi_{(i,t)}$), fixed operation ($\pi_{(i,t)}$), for boiler and turbine units.
- Given fuel cost $\xi_{(i,t)}$ for each boiler and fuel calorific value Cq_t.
- Given penalty terms for electricity purchases (λ_t^{buy}) and excessive electricity production (λ_t^{ex}).
- Given penalty terms for heat purchases ($\mu_{(j,t)}^{buy}$) and heat disposal ($\mu_{(j,t)}^{ex}$), for each heat network.
- Given penalty terms for operating a turbine in its lower or upper extreme region ($\rho_{(i,t)}^{-}$ or $\rho_{(i,t)}^{+}$).

For each time period, the administrator of the CHP plant needs to take main decisions regarding to:

- The operating status of each boiler and turbine unit (i.e., idle, startup, operating, shutdown).
- The maintenance status of each boiler and turbine unit (i.e., under maintenance or not).
- The operating regions of operating turbine units (i.e., desired or extreme operating regions).
- The operating level of each boiler and turbine unit.
- The outlet heat flow of each turbine unit.
- The heat flows that bypass the turbines (through the RCUs) and go directly to the heat networks.
- The deviation from the electricity demand (i.e., electricity purchases or excessive electricity production).
- The deviation from the heat demand of each heat network (i.e., heat purchases or heat disposal).

by considering the minimization of total cost that consists of costs related to startup, operation, shutdown and maintenance of boiler and turbine units as well as fuel costs in addition to penalties for deviation from heat and electricity demands.

3.2.1 Optimization Framework for case study of Karaganda Utility System

In this section, a mathematical programming model is presented for the simultaneous planning of operational and maintenance tasks in combined heat and power plants as those described in Section 3.2 of the KUS plant model layout. To facilitate the presentation of the proposed model, uppercase Latin letters for optimization variables and sets, and lowercase Greek letters for most of the parameters have been used. The description of the proposed optimization framework follows.

3.2.2 Generation level bounds for boiler and turbine units and heat balance in the steam pipeline

To model the generation levels for boiler and turbine units, we introduce operating binary variables $X_{(i,t)}$ that denote if a unit is operating (i.e., $X_{(i,t)} = 1$) or not (i.e., $X_{(i,t)} = 0$) during time period t. Constraints (1) provide lower ($\theta_{(i,t)}^{min}$) and upper ($\theta_{(i,t)}^{max}$) bounds on the heat generation level $Q_{(i,t)}^{B}$ for any boiler unit $i \in I^B$. In the same line, constraints (2) impose lower ($\varepsilon_{(i,t)}^{min}$) and upper ($\varepsilon_{(i,t)}^{max}$) bounds on the electricity generation level ($E_{(i,t)}^{T}$) for any turbine unit $i \in I^T$. In addition, the outlet heat from a turbine unit $Q_{(i,t)}^{Tout}$ should be below a maximum value $\theta_{(i,t)}^{Tmax}$, as modeled by constraints (3). Finally, constraints (4) represent the heat balance in the main steam pipeline. Non-negative variables $H_{(j,t)}^{RCU}$ denote the associated heat sent to the reduction-cooling units (Figure 3-1).

$$\theta_{(i,t)}^{min} X_{(i,t)} \leq Q_{(i,t)}^{B} \leq \theta_{(i,t)}^{max} X_{(i,t)} \quad \forall i \in I^B, t \in T \tag{3-1}$$

$$\varepsilon_{(i,t)}^{min} X_{(i,t)} \leq E_{(i,t)}^{T} \leq \varepsilon_{(i,t)}^{max} X_{(i,t)} \quad \forall i \in I^{T}, t \in T \tag{3-2}$$

$$Q_{(i,t)}^{Tout} \leq \theta_{(i,t)}^{Tmax} X_{(i,t)} \quad \forall i \in I^{T}, t \in T \tag{3-3}$$

$$\sum_{i \in I^{B}} (1 - loss_{i})\, Q_{(i,t)}^{B} = \sum_{i \in I^{T}} Q_{(i,t)}^{Tin} + \sum_{j \in J} H_{(j,t)}^{RCU} \quad \forall t \in T \tag{3-4}$$

3.2.3 Extreme operating regions for turbine units

Constraints (2) define the desired operating region for each turbine unit through lower and upper bounds on the electricity generation level. This desired operating region ensures a stable operation for the turbine unit. However, in some cases operation out of this region may be allowed. In that case constraints (2) should be replaced by the following set of constraints (5):

$$\begin{aligned}
&\Delta\varepsilon_{(i,t)}^{-} X_{(i,t)} \leq E_{(i,t)}^{T} \leq \Delta\varepsilon_{(i,t)}^{+} X_{(i,t)} \quad \forall i \in I^{T}, t \in T \\
&\varepsilon_{(i,t)}^{min} - M(1 - Y_{(i,t)}) \leq E_{(i,t)}^{T} \leq \varepsilon_{(i,t)}^{max} + M(1 - Y_{(i,t)}) \quad \forall i \in I^{T}, t \in T \\
&\Delta\varepsilon_{(i,t)}^{-} - M(1 - Y_{(i,t)}^{-}) \leq E_{(i,t)}^{T} < \varepsilon_{(i,t)}^{min} + M(1 - Y_{(i,t)}^{-}) \quad \forall i \in I^{T}, t \in T \\
&\varepsilon_{(i,t)}^{max} - M\left(1 - Y_{(i,t)}^{+}\right) < E_{(i,t)}^{T} \leq \Delta\varepsilon_{(i,t)}^{+} + M(1 - Y_{(i,t)}^{+}) \quad \forall i \in I^{T}, t \in T \\
&Y_{(i,t)}^{-} + Y_{(i,t)} + Y_{(i,t)}^{+} = X_{(i,t)} \quad \forall i \in I^{T}, t \in T
\end{aligned} \tag{3-5}$$

Parameters $\Delta\varepsilon_{(i,t)}^{-}$ and $\Delta\varepsilon_{(i,t)}^{+}$ define the additional allowable operating regions lower than $\varepsilon_{(i,t)}^{min}$ and higher than $\varepsilon_{(i,t)}^{max}$ of the desired operating region, as shown in Figure 3-2 Parameter M is a very large number. Binary variables $Y_{(i,t)}^{-}$, $Y_{(i,t)}$, and $Y_{(i,t)}^{+}$ are introduced to identify if the turbine unit operates in the extreme lower operating region, the desired operating region, or the extreme upper operating region, respectively. These binary variables are then linked to the operating binary variable $X_{(i,t)}$ through the last line of constraints. In addition to these constraints, a penalty term needs to be added to the objective function of the optimization problem to penalize operation in extreme regions and thus favor operation within the desired operating region.

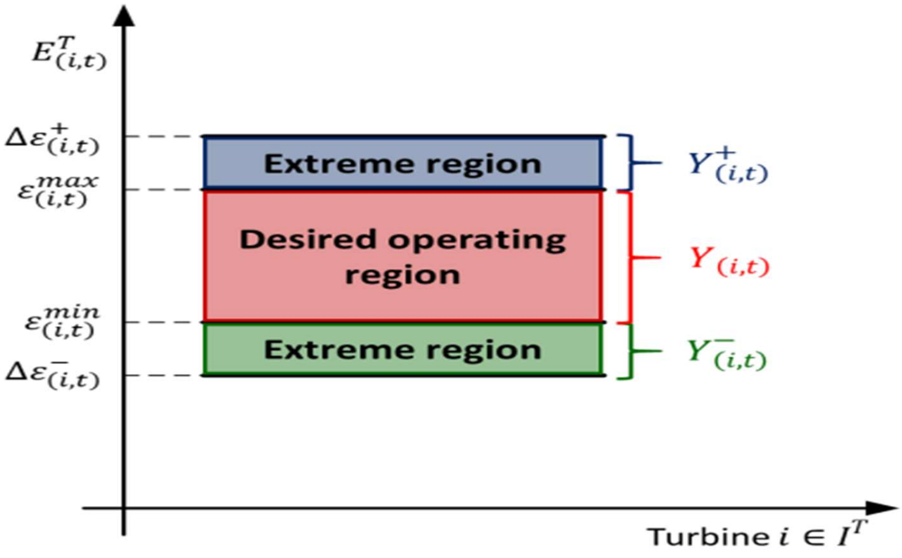


Figure 3-2 Operating regions for turbine units.

3.2.4 Electricity and heat balance in turbine and boiler units (energy demand)

The heat balance for each turbine $i \in I^T$ is defined by considering the inlet heat to the turbine $Q^{Tin}_{(i,t)}$, the generated electricity $E^T_{(i,t)}$ from the turbine, the outlet heat $Q^{Tout}_{(i,t)}$ from the turbine and its efficiency $\eta_{(i,t)}$, as given by:

$$Q^{Tin}_{(i,t)} = \frac{E^T_{(i,t)}}{\eta_{(i,t)}} + Q^{Tout}_{(i,t)} \quad \forall i \in I^T, t \in T \tag{3-6}$$

Constraints (7) represent the electricity balance of the system for the satisfaction of the electricity demand. For every time period, this electricity balance ensures that the total electricity generated from the turbine units plus the electricity purchases E^{buy}_t are equal to the overall electricity demand ζ^{el}_t (considering also the electricity demand of the internal system, given by factor β^E_t) plus the extra electricity generation E^{ex}_t. Constraints (8) represent the heat balance in each heat network for the satisfaction of its total heat demand. For each heat network and time period, the heat balance ensures that the outlet heat of all turbine units connected to the heat network ($i \in I^T_j$) plus the total outlet heat of the reduction-cooling units and heat purchases ($H^{buy}_{(j,t)}$) are equal to the heat demand $\zeta^{hea}_{(j,t)}$ of the corresponding heat network plus the heat disposed $H^{ex}_{(j,t)}$.

$$\sum_{i \in I^T} E_{(i,t)}^{T} + E_t^{buy} = (1 + \beta_t^E)\, \zeta_t^{el} + E_t^{ex} \quad \forall t \in T \tag{3-7}$$

$$H_{(j,t)}^{buy} + \eta_j^{RCU} H_{(j,t)}^{RCU} + \sum_{i \in I_j^T} Q_{(i,t)}^{Tout} = (1 + \beta_t^H)\, \zeta_{(j,t)}^{heat} + H_{(j,t)}^{ex} \quad \forall j \in J, t \in T \tag{3-8}$$

Furthermore, if there are no external sources available for acquiring energy (electricity or heat), then the corresponding variables represent unsatisfied energy demands.

3.2.5 Startup and shutdown action for boiler and turbine units

For any boiler and turbine unit, constraints (3-9) and (3-10) determine startup and shutdown actions at each time point t through the operating binary variables $X_{(i,t)}$ of any two consecutive periods. Constraints (3-10) ensure that startup and shutdown actions cannot occur at the same time in any boiler or turbine unit i. For $t = 0$, $X_{(i,0)}$ is a known parameter that describes the initial state of the operational status for each unit just before the beginning of the time horizon considered and ‘t-1’ is the time horizon before “t”.

$$S_{(i,t)} - F_{(i,t)} = X_{(i,t)} - X_{(i,t-1)} \quad \forall i \in I, t \in T \tag{3-9}$$

$$S_{(i,t)} + F_{(i,t)} \leq 1 \quad \forall i \in I, t \in T \tag{3-10}$$

3.2.6 Minimum run and idle times for boiler and turbine units

Boiler and turbine units are subject to minimum run and idle periods (ω_i and ψ_i, respectively) constraints, which are modeled by:

$$\sum_{t'=\max\{1, t-\omega_i+1\}}^{t} S_{(i,t')} \leq X_{(i,t)} \quad \forall i \in I, t \in T \tag{3-11}$$

$$\sum_{t'=\max\{1, t-\psi_i+1\}}^{t} F_{(i,t')} \leq 1 - X_{(i,t)} \quad \forall i \in I, t \in T \tag{3-12}$$

3.2.7 Maximum runtimes for boiler and turbine units

Constraints (13) impose an upper limit to the total number of time periods t in which a unit i has been continuously online since its last startup (i.e., maximum runtime δ_i). To carry over relevant information from the past time horizon, initial state constraints (14) are introduced that consider the total number of time periods at the end of the previous time horizon in which unit i has been continuously online since its last startup (γ_i).

$$\sum_{t'=\max\{1,t-\delta_i\}}^{t} X_{(i,t')} \leq \delta_i \quad \forall i \in I, t \in T \tag{3-13}$$

$$\sum_{t'=\max\{1,t-\delta_i+\gamma_i\}}^{t} X_{(i,t')} \leq \delta_i - \gamma_i \quad \forall i \in I, t \in T: t = \delta_i - \gamma_i + 1, \gamma_i > 1 \tag{3-14}$$

3.2.8 Maintenance for boiler and turbine units: flexible time-windows policy

Major maintenance tasks for boiler and turbine units are typically predefined (i.e., starting and finishing times of maintenance tasks are fixed) before the optimization of the energy production plan of the energy generation plant. The durations ν_i of maintenance tasks are generally known. In this study, we consider flexible maintenance tasks that should start (i.e., $W_{(i,t)} = 1$) within a predefined time window $[\tau_i^{min}, \tau_i^{max}]$, and their actual starting times are additional decisions to be optimized. The following sets of constraints are used for boiler and turbine units that are subject to flexible time-window maintenance:

$$\sum_{\substack{t \geq \tau_i^{min} \\ t \in T}}^{\tau_i^{max}} W_{(i,t)} = 1 \quad \forall i \in I \tag{3-15}$$

$$X_{(i,t)} + \sum_{t'=\max\{\tau_i^{min}, t-\nu_i+1\}}^{\min\{\tau_i^{max}, t\}} W_{(i,t')} \leq 1 \quad \forall i \in I, t \in T \tag{3-16}$$

However, predefined maintenance tasks (i.e., fixed starting time) could be also modeled by simply setting $\boldsymbol{\tau_i^{min}} = \boldsymbol{\tau_i^{max}}$.

3.2.9 Objective function

The optimization goal in this industrial-driven case study is to minimize the annual total cost of the cogeneration plant, as given by equation (17). More specifically, the total cost considers startup and shutdown costs, fixed operating and fuel costs, maintenance costs, penalties for deviation from heat and electricity demands, and penalties for turbines for operating outside the desired operating regions.

$$
\begin{aligned}
&\min Cost = && \text{Total cost (to be minimized)} \\
&\sum_{t\in T}\sum_{i\in I}\big(\alpha_{(i,t)}S_{(i,t)} + \varphi_{(i,t)}F_{(i,t)}\big) && \text{Startup and shutdown costs for boiler and turbine units} \\
&+\sum_{t\in T}\sum_{i\in I}\big(\pi_{(i,t)}X_{(i,t)}\big) && \text{Fixed operating costs for boiler and turbine units} \\
&+\sum_{t\in T}\sum_{i\in I^B}\left(\frac{\xi_{(i,t)}\ Q^B_{(i,t)}}{\eta_{(i,t)}Cq_t}\right) && \text{Heat generation costs for boilers (i.e., fuel cost)} \\
&+\sum_{t\in T}\sum_{i\in I}\big(\kappa_{(i,t)}W_{(i,t)}\big) && \text{Maintenance costs for boiler and turbine units} \\
&+\sum_{t\in T}\sum_{j\in J}\Big(\mu^{buy}_{(j,t)}H^{buy}_{(j,t)} + \mu^{ex}_{(j,t)}H^{ex}_{(j,t)}\Big) && \text{Penalties for deviation from heat demands} \\
&+\sum_{t\in T}\sum_{i\in I^T}\big(\lambda^{buy}_t E^{buy}_t + \lambda^{ex}_t E^{ex}_t\big) && \text{Penalties for deviation from electricity demand} \\
&+\sum_{t\in T}\sum_{i\in I^T}\big(\rho^-_{(i,t)}Y^-_{(i,t)} + \rho^+_{(i,t)}Y^+_{(i,t)}\big) && \text{Penalties for turbines for operating in extreme regions}
\end{aligned}
\tag{3-17}
$$

3.2.10 Case Study of Karaganda Utility System (KUS)

The proposed optimization framework has been used to solve the simultaneous planning of operational and maintenance tasks in the KUS CHP plant, which is the largest coal-fired CHP plant of Kazakhstan with an installed power capacity of 670MW and a total thermal capacity equal to 1,058 Gcal/h. The plant consists of eight boilers (B1-B8), six turbines (T1-T6) and two RCUs. The KUS CHP plant layout has been described in Section 3 (see Fig. 3-1). Each boiler unit consumes 70 ton/h of high-ash coal with low calorific value (Cq_t =3,980 kcal/kg). Coal cost is low ($\xi_{(i,t)}$=$6/ton). Boilers B1 to B7 are of type 'BKZ-420-140' and have a lower and maximum heat generation level equal to 145.3 MW and 290.6 MW, respectively. Boiler B8 is of type 'HG-670/14y-YM20' and has a lower and maximum heat generation level equal to 231.3 MW and 464.9 MW, respectively. The heat losses coefficient due to the combustion loss/unburned fuel for all boiler units is equal to 2%. Startup and shutdown costs for boilers are equal to $3,230 and $2,422, respectively. To specify the feasible operating regions for turbines, steam consumption relations between thermal output and electricity generation have been analyzed though extensive sets of historical data of the KUS CHP plant. The operating bounds for desired and extreme operating regimes as well as the maximum outlet heat flows for all turbines are given in Table 3-1. Startup and shutdown costs for turbines are equal to $916 and $458, respectively. The average monthly efficiency has been considered for each turbine. RCU efficiencies are equal to 10%. For all boiler and turbine units, minimum runtimes are $\omega_i = 2$ days, and minimum idle times are $\psi_i = 1$ day.

Table 3-1 Operating levels bounds for desired and extreme operating regions and maximum outlet heat flows for turbines

Turbine	min desired regime $\varepsilon^{min}_{(i,t)}$ (MW)	max desired regime $\varepsilon^{max}_{(i,t)}$ (MW)	min extreme regime $\Delta\varepsilon^{-}_{(i,t)}$ (MW)	max extreme regime $\Delta\varepsilon^{+}_{(i,t)}$ (MW)	max outlet heat flow $\theta^{Tmax}_{(i,t)}$ (MW)
T1	66.0	110.0	55.0	115.0	203.4
T2	66.0	110.0	22.0	110.0	203.4
T3	66.0	110.0	38.0	115.0	203.4
T4	66.0	110.0	34.0	120.0	203.4
T5	72.0	120.0	48.0	135.0	218.5
T6	66.0	110.0	33.0	110.0	197.6

Table 3-2 includes the main data for the maintenance of boiler and turbine units along with the starting times of the implemented maintenance plan by the industry, representing the recording of the actual operation of the power plant. Additionally, presented recordings are for the year 2015 and as such, the values reported for the earliest start of maintenance are equivalent to the corresponding days of the year. For example, day 125 for unit B1 corresponds to 05/05/2015, the 125th day of that year, and the trend continues in that manner.

Moreover, as research could have an impact only when it is applied to the relevant industries, in practice, the graphical user interface (GUI) developed will allow the user to run simulation studies through the optimization model and enhance their decision making process.

Additionally, the annual operational and maintenance planning in an industrial large-scale CHP plant was studied A total time horizon of one year divided in 365 daily time periods was considered. This is a common and valid approach for all relevant case studies, as one could see in the open literature as well. To clarify, the results of the proposed model support the decision to be taken for the annual maintenance plan and give a good idea about the annual operational plan for boilers and turbines. Saying that, the plans obtained are not the actual daily plans applied in reality, but managers would prefer at least to follow the optimized annual maintenance plans. Having the obtained information and real-time information in daily or even hourly-basis, the plant manager defines the detailed daily schedule.

Dealing with uncertainty is out of the scope of this work. Here, an efficient deterministic optimization model is developed and presented for the problem in question. However, it is worthy to note that uncertainty (e.g., units breakdowns, energy demand fluctuations, etc.) are very important issues that should be addressed properly in the real scenario. Moreover, the changes happening during the year will affect the annual operational and maintenance plans in place, and this is the case for any other type of uncertainty. For this reason, it is agreed that uncertainty and also demand response studies are very important aspect of the real problem which will be dealt with separately in future work, because they require a large number of further developments which constitute further research activities

Furthermore, current work may be improved by devising stochastic programming approaches based on the presented deterministic model to deal effectively with a variety of types of uncertainty. Addressing uncertainty in this problem results in very large-scale stochastic programming problems that in order to be solved requires the development of efficient and complex decomposition techniques, thereby bridging the gap between planning, scheduling and plant operations.

Table 3-2 Maintenance data (including starting times for actual KUS solution)

Unit	Type	$\kappa_{(i,t)}$ (maintenance cost) ($)	ν_i (duration of maintenance task) (days)	τ_i^{min} (earliest start of maintenance) (day)
B1	TM	20,000	29	125
B2	TM	20,000	25	195
B3	MO	153,729	88	107
B4	TM	20,000	19	176
B5	MO	111,966	74	224
B6	TM	20,000	31	237
B7	TM	20,000	11	161
T1	TM	10,000	20	20
T2	TM	10,000	16	148
T3	MO	41,815	88	205
T4	MO	106,269	11	301
T5	EM	30,415	41	161

Additionally, Table 3-2 gives detailed information about the type of maintenance at each unit. In as much as the distinction between the different types of maintenance reported at the power plant does not have any impact on the proposed model, it is worth noting that the different maintenance plans adopted impacted the model, thereby leading to a suggested reduction in the overall cost of the CHP plant.

More specifically, the following three types of maintenance are reported: Typical Maintenance (TM), Extended Maintenance (EM), and Major Overhaul (MO). In general, EM has a longer duration and higher cost than TM, and usually involves the replacement of important parts of the equipment (around 50% replacement of parts). EM usually takes place in a unit once every 2-3 years. MO typically occurs in a unit once every 4-6 years and usually needs high maintenance durations. MO is the most expensive type of maintenance that involves the replacement of most parts of the equipment (around 90% replacement of parts).

A total time horizon of one year divided in 365 daily periods was considered. Figure 3-3 displays the annual demand profile for electricity and the annual heat demand profiles for the two heat networks connected to the KUS CHP plant. These are real energy demand data for year 2015. In addition, there are some electricity requirements for the use of internal equipment of the plant (e.g., coal crushers, pumps, compressors, blowers). These internal electricity requirements are given by $\beta_t^E = 12.5\%$; lower than that of other CHP plants in Kazakhstan (usually within 13-15%). The internal heat requirements of the plant are given by $\beta_t^H = 2\%$. Finally, it should be mentioned that boiler B8 and turbine T6 have been installed in 2015 and they became available for limited operation (allowing to reach at most half of their installed capacity) only in the last month of the year.

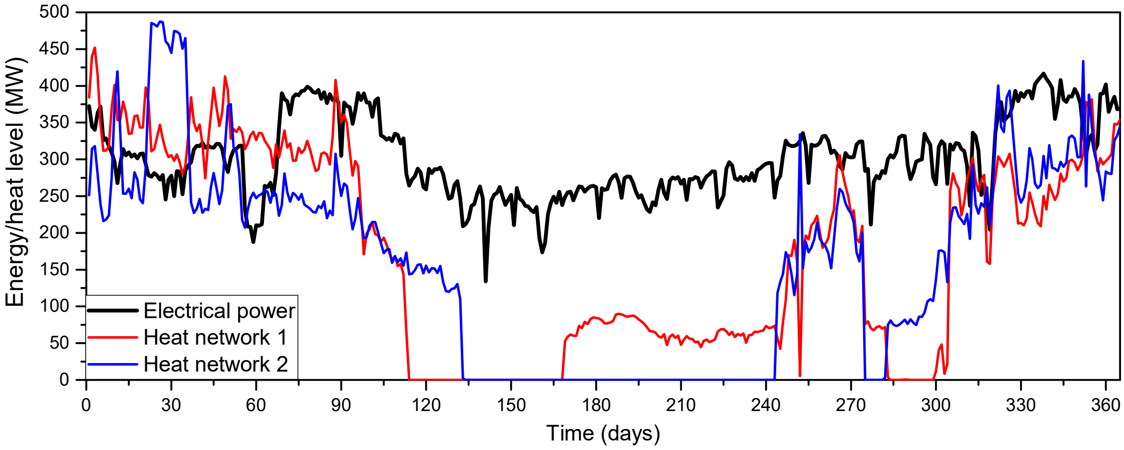


Figure 3-3 Annual profiles for electricity demand and heat demand per heat network (MW).

In order to reduce over dependency on imported fuel, thereby raising the level of energy security of an economy, and reduce emissions in ESC which are mainly caused by fossils, consideration is given to renewables integration in fossil fuel supply chain.

3.3 Karaganda Utility System (KUS) results, analysis and discussion

With consideration given to the case study of Karaganda Utility System (KUS), a detailed comparison is presented among the solutions obtained by the proposed optimization approach and the solution implemented by the industry (i.e., KUS CHP plant). More specifically, we solve, analyze and compare the following set of solution approaches:

KUS: energy production and maintenance plan implemented by the KUS CHP plant (industrial solution).

OPT-1: optimized energy production through a fixed maintenance policy (i.e., same maintenance plan with KUS solution, thus fixed maintenance time-windows).

OPT-2: optimized energy production and maintenance plan considering flexible time-windows of limited range (i.e., earliest and latest starting maintenance time one month before and after than the fixed time of the KUS solution).

OPT-3: optimized energy production and maintenance plan considering completely flexible time-windows (i.e., maintenance can occur at any time within the year).

All optimization problems have been solved in GAMS/CPLEX 12.6 in an Intel(R) Core(TM) i7-6700 CPU under standard configurations and a zero optimality gap. Solutions are obtained in negligible computational times.

Figure 3-4 and Figure 3-5 display the maintenance plans for boilers and turbines for all solution approaches. Notice that the maintenance plan for OPT-1 is identical to that of KUS. It is observed that the maintenance tasks for all turbines in OPT-2 start and finish before those reported by KUS. The same trend is observed for the maintenance of most boilers, but B1 and B6. OPT-3 reports a maintenance plan that differs significantly from that of KUS. It is clear that the simultaneous optimization of maintenance and energy production generates maintenance plans that are considerably different than those obtained by following a predefined maintenance approach and solve the energy production planning in a second stage (i.e., KUS).

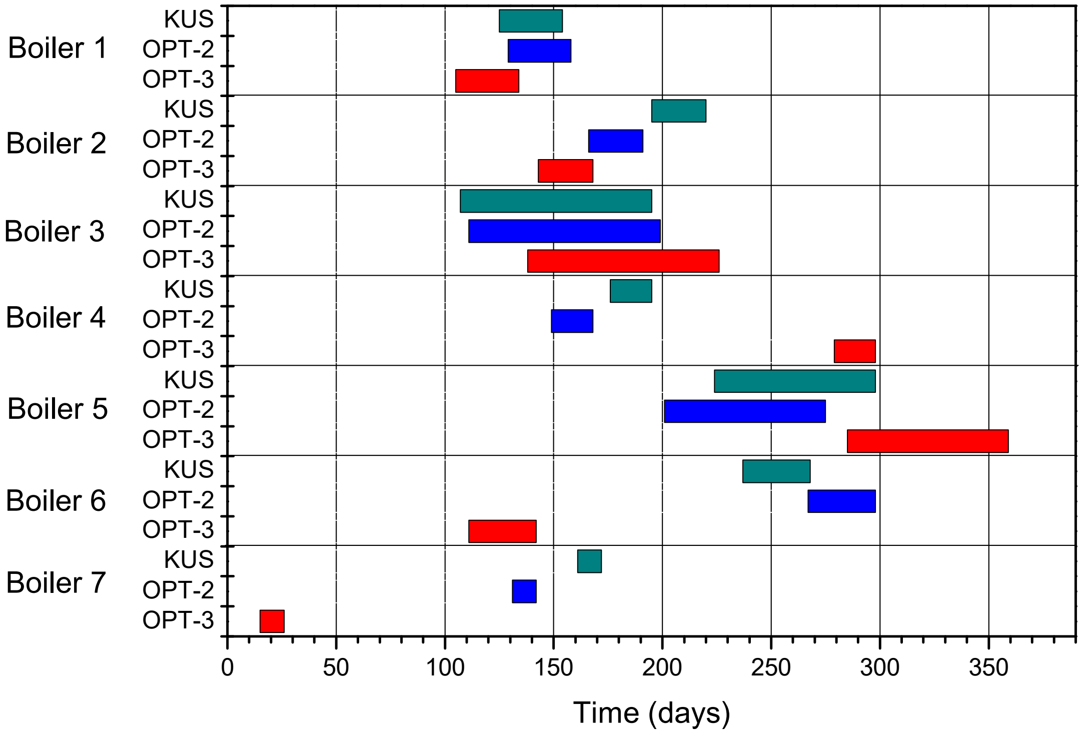


Figure 3-4 Maintenance plans for boilers for all solution approaches.

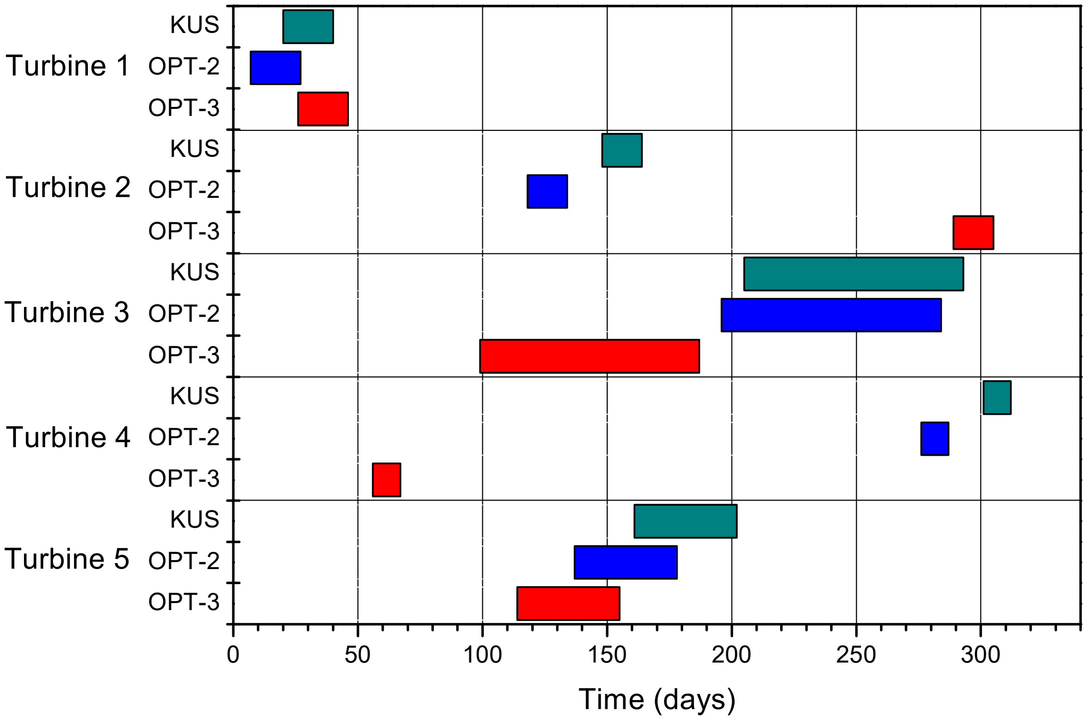


Figure 3-5 Maintenance plans for turbines for all solution approaches.

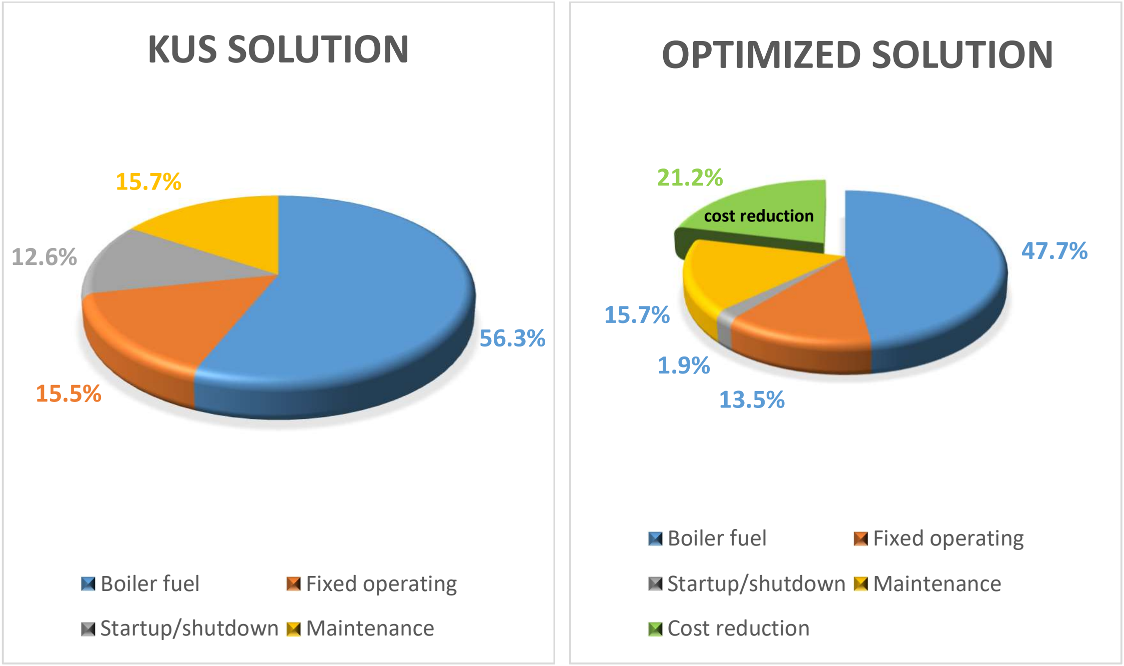


Figure 3-6 Comparison of annual total cost breakdown between KUS and OPT-3 (%)

Figure 3-6 displays the annual total cost breakdown comparison between the industrial KUS solution and the solution obtained by our proposed approach OPT-3. A remarkable reduction in the annual total cost of 21.2% is reported by the optimization-based OPT-3 solution. Also, OPT-1 and OPT-2 report a reduction in total cost above 20% compared to that of KUS solution. Recall that the same maintenance tasks need to take place in all approaches, for this reason the maintenance cost contribution is the same for all solution approaches. As shown in Figure 3-7, in comparison to the KUS solution, the OPT-3 solution results in a decrease in: (i) fuel costs by 15.2%; (ii) fixed operating costs by 12.7%; and (iii) startup/shutdown costs by 84.7%. These show clearly that optimization approaches achieve to: (i) avoid unnecessary startups and shutdowns of boiler and turbine units; and (ii) decrease significantly the fuel consumption, and still fully satisfying the energy demands.

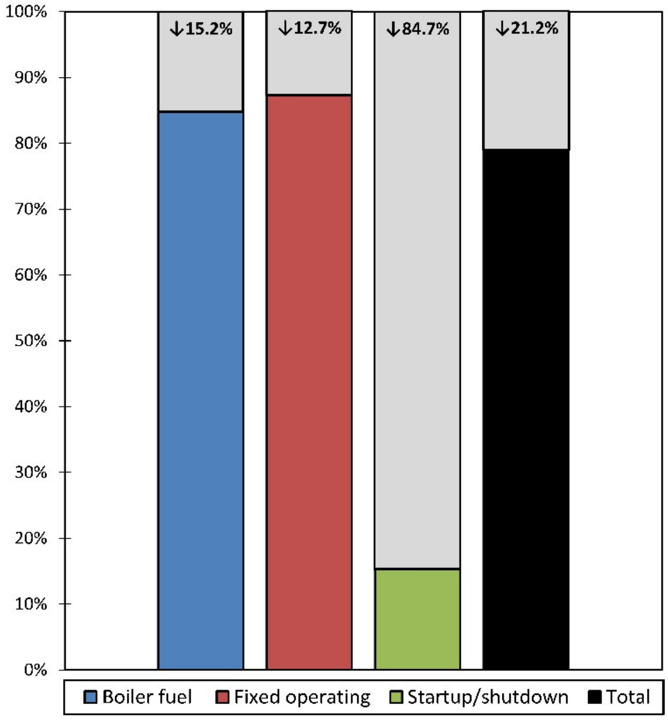


Figure 3-7 Cost terms for OPT-3 compared to those of KUS solution

Figure 3-8 displays the aggregated total cost profiles for KUS, OPT-2 and OPT-3 solution approaches. It shows how the total cost difference increases over time among the optimized and the industrial solution.

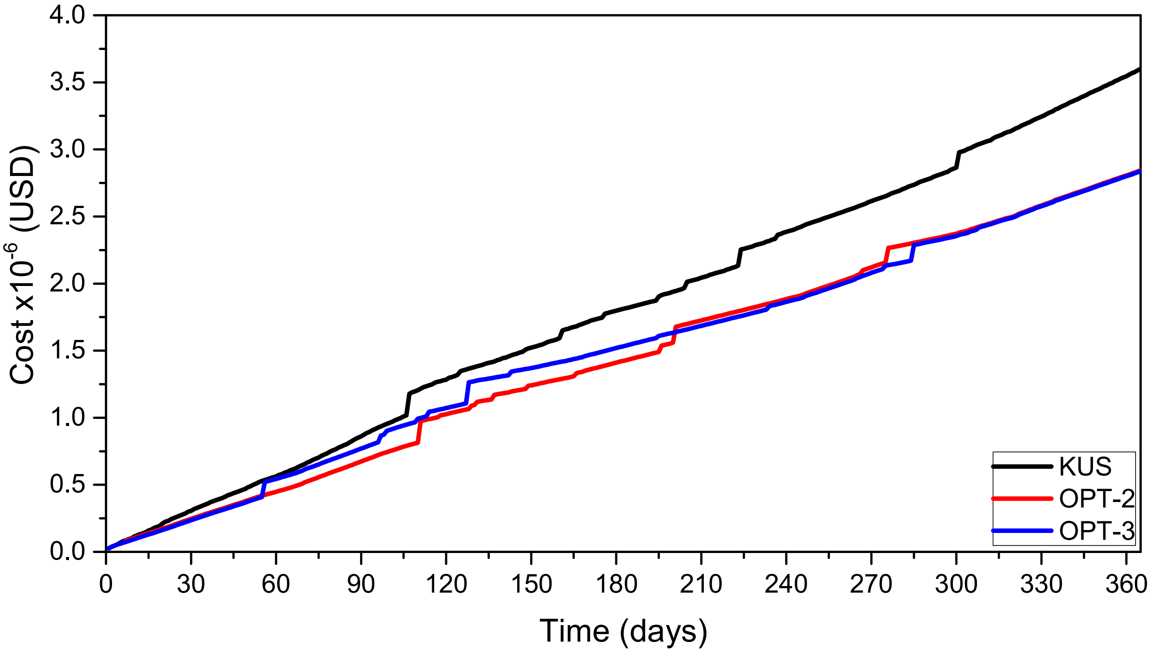


Figure 3-8 Aggregated total cost profiles for KUS solution and optimized solutions OPT-2 and OPT-3.

The left part of Figure 3-9a and Figure 3-9b show the annual operating load profiles for all turbines for the KUS solution. These are normalized profiles with respect to the upper bound of the desired operating region of each turbine. Saying that, operating loads between 60% and 100% represent desired regions of operation while operating loads above 100% or below 60% correspond to operation in extreme regions. In KUS solution, it can be seen that most turbines operate in extreme regions along the planning horizon considered. Especially, turbines 1, 3, 4 and 5 operate in the upper extreme region in many time periods. Turbines 2, 3, 4 and 5 operate in the lower extreme region for a very limited number of time periods. The right part of Figure 3-9a and Figure 3-9b shows a comparison of the annual operating load profiles for all turbines for the OPT-3 solution with respect to those of the KUS solution. More specifically, the figures on the right part of Figure 3-9a and Figure 3-9b display the profile of the deviation of the operating loads of OPT-3 having as a reference the operating loads reported by the KUS solution (i.e., figures on the left part). The red line on the figures on the right part corresponds to the KUS solution operating load levels shown on the corresponding figures on the left. Energy demands are completely satisfied in both solution approaches. The most significant fact is that OPT-3 solution does not report operation of turbines in extreme regions at any time period. Operation in extreme regions affects importantly the efficiency and the performance degradation of the turbine, increase the possibility of mechanical damage, and in the longer-term could reduce considerably the life-time of the equipment. On average, OPT-3 reports lower total operating loads throughout the planning horizon considered, contributing to the reduction in fuel consumption. Recall that turbine 6 is available only in the last month of the year and can operate in half its maximum capacity. OPT-3 solution prefers not to operate at all turbine 6, since the electricity demand in that month can be met by the other turbines.

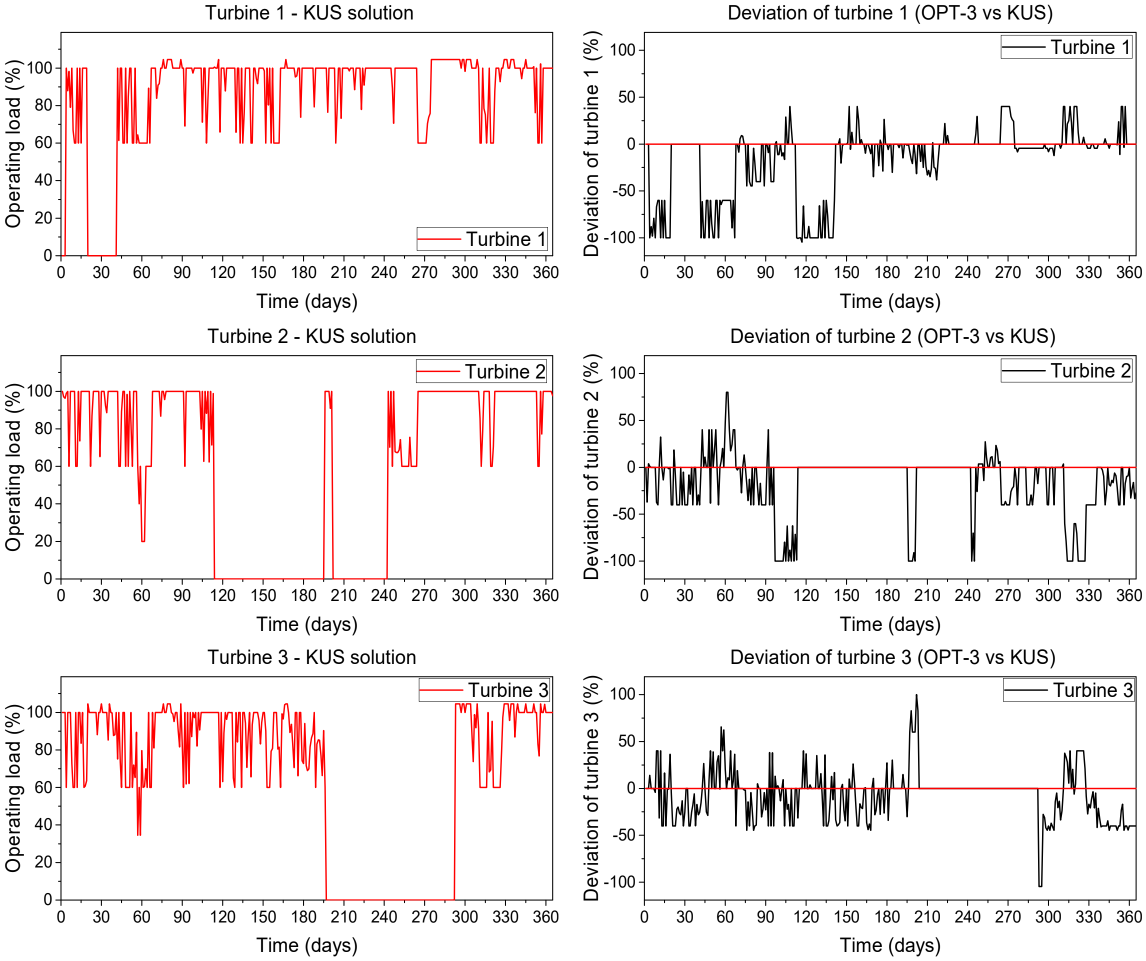


Figure 3-9a Turbines 1 to 3. Normalized operating load profile for KUS solution (figures on the left), and operating load deviation profile for OPT-3 from KUS solution (figures on the right).

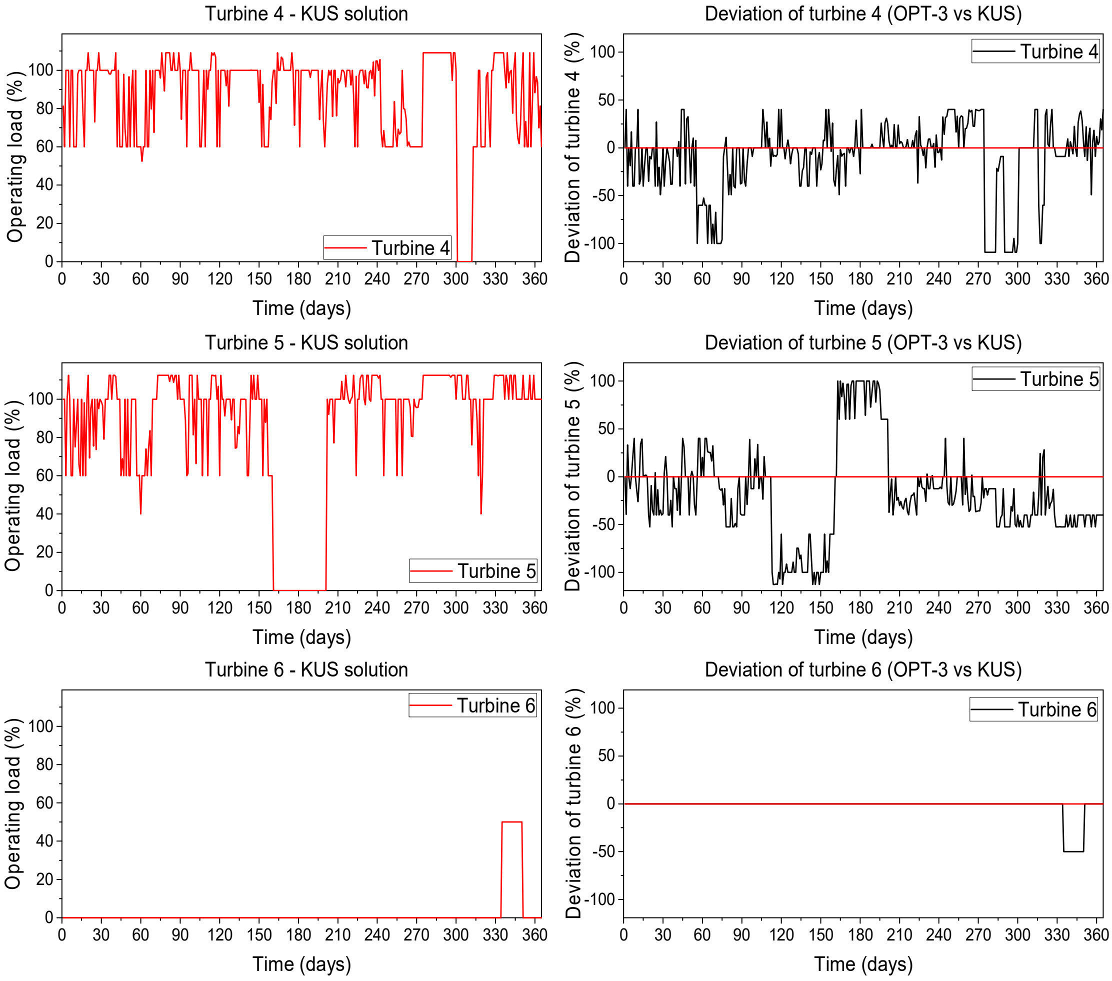


Figure 3-9b. KUS vs OPT-3: Turbines 4 to 6. Normalized operating load profile for KUS solution (figures on the left), and operating load deviation profile for OPT-3 from KUS solution (figures on the right).

In the same line with Figure 3-9a and Figure 3-9b , Figure 3-10a and Figure 3-10b display the relevant operating load information for all boiler units along with a comparison of them between the KUS and OPT-3 solutions. Boiler 8 is available only in the last month of the year, but it is not used in any of the two solutions, and for this reason it is not presented in those figures. The left part of Figure 3-10a and Figure 3-10b display the annual operating load profiles for all boiler for the KUS solution, normalized profiles with respect to the maximum heat generation level of each boiler. The figures on the right part of Figure 3-10a and Figure 3-10b display the profile of the deviation of the operating loads of the OPT-3 solution having as a reference the operating loads reported by the KUS solution (i.e., figures on the left part). The red line on the figures on the right part corresponds to the KUS solution operating load levels shown on the corresponding figures on the left. It is observed that boilers 1 and 7 are not used in OPT-3 solution as much as in KUS. This is basically due to the associated technical characteristics and operating costs for these boilers, as also confirmed by the industry. Important deviations on the operating levels for boiler 2 and 3 are observed between the KUS and the OPT-3 solution, but overall heat generation levels are comparable. In general, the OPT-3 solution reports higher overall heat generation levels for boilers 4 to 6 in comparison to those in the KUS solution.

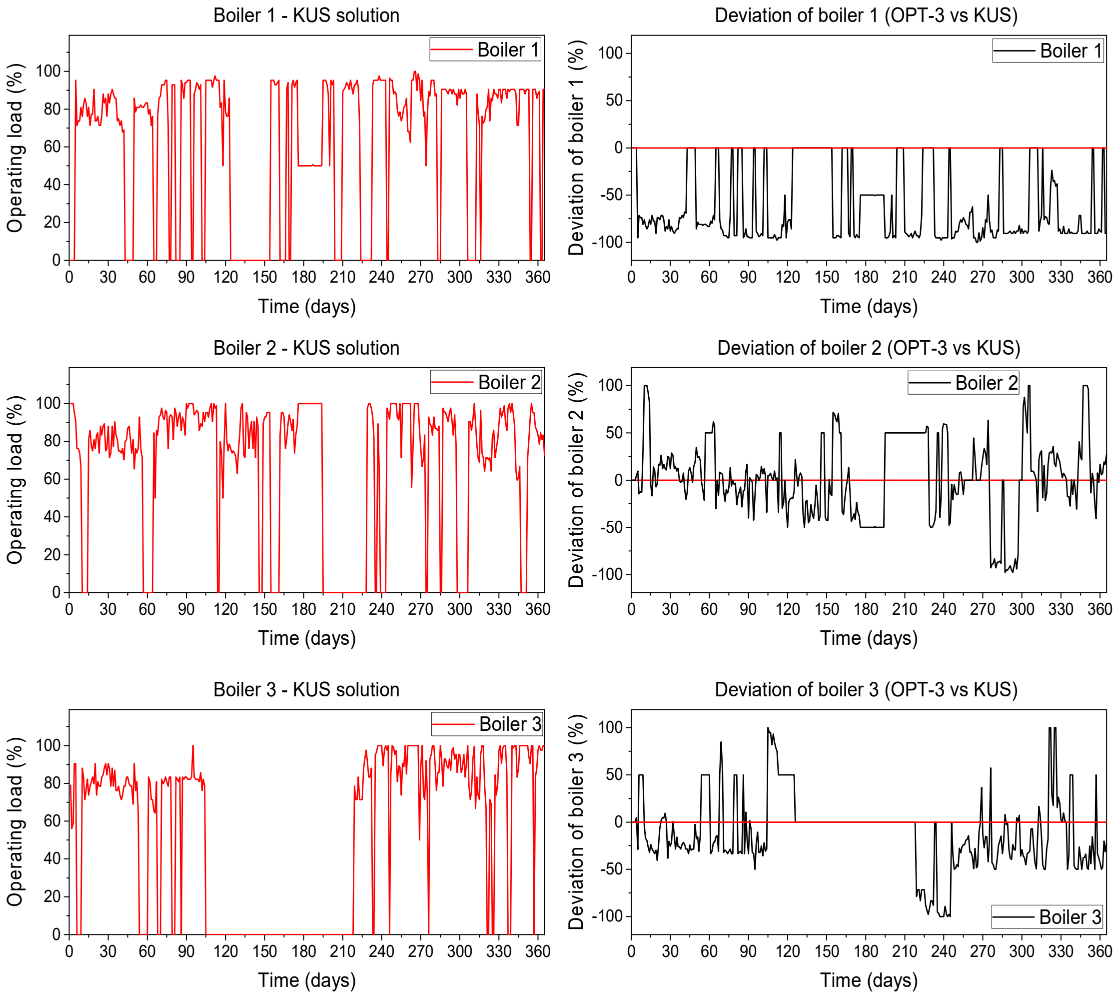


Figure 3-10a Boilers 1 to 3. Normalized operating load profile for KUS solution (figures on the left), and operating load deviation profile for OPT-3 from KUS solution (figures on the right).

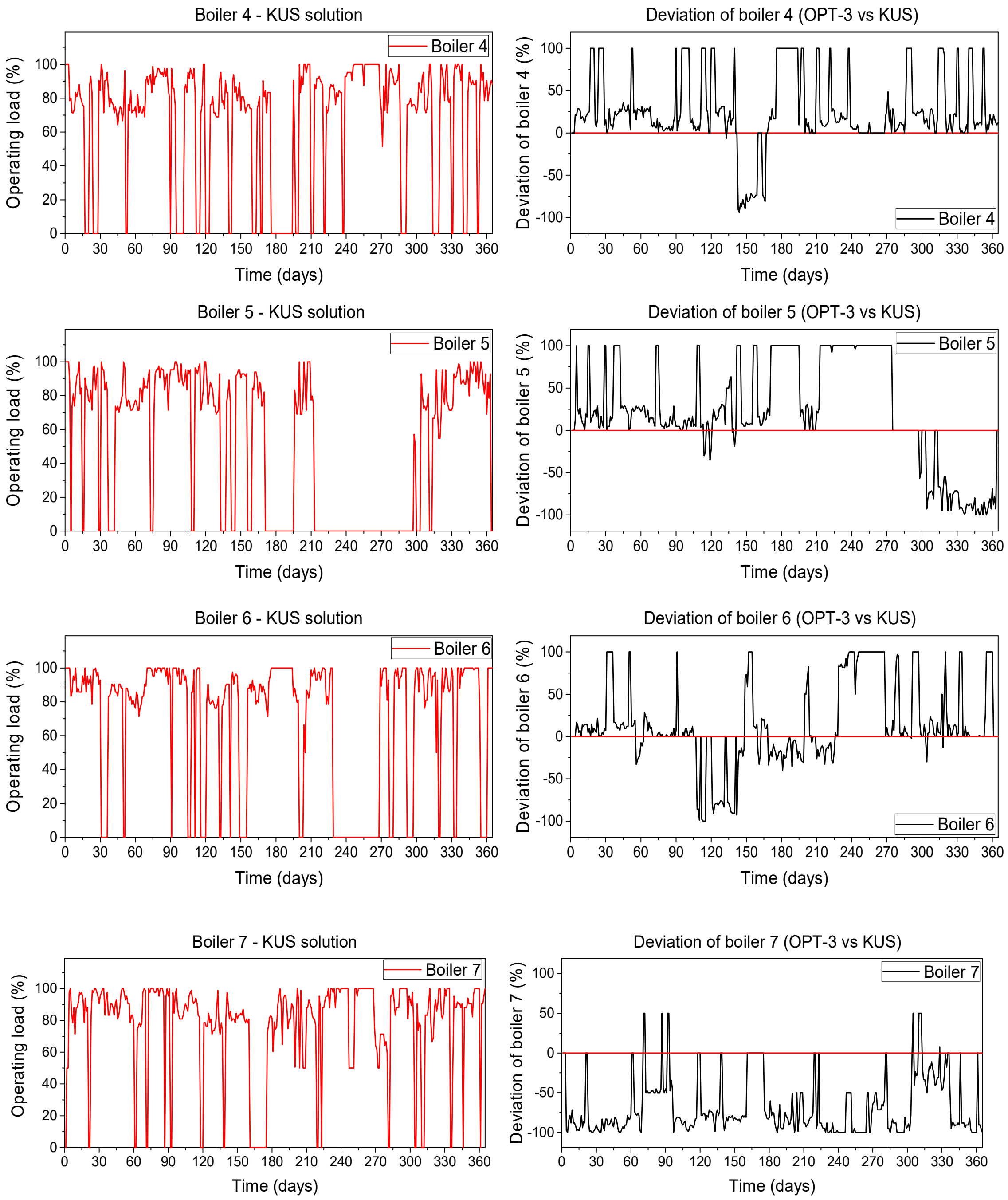


Figure 3-10b. Boilers 4 to 7. Normalized operating load profile for KUS solution (figures on the left), and operating load deviation profile for OPT-3 from KUS solution (figures on the right).

All results presented here have been validated by the industry, and it has been recognized that the proposed optimization framework can generate energy production and maintenance plans that result in remarkable reductions in total costs and enhanced energy efficiency of the cogeneration plant. The proposed approach constitutes a systematic way for the better coordination of energy production and maintenance tasks that could be the main core of an optimization-based decision support tool enclosed within a user-friendly graphical user interface to be used directly by the industry. Moreover, the model development will allow the user to run simulation studies through the presented optimization model and enhance their decision making process. Additionally, the optimal solution is better because it achieves about 21% total cost reduction over the annual operation of the CHP plant (please refer to Fig. 3-6). In addition, operation in extreme regions for turbines is avoided as discussed in the presentation of the results. This is very important and in the long-term would increase the life-time of the turbine units which are major capital assets for any CHP plant.

4 DESCRIPTION ON THEORY AND METHODS OF BIOMASS CO-FIRING WITH COAL

With a further consideration given to biomass in the second case study, biomass is known to be a low-density material that could be lost during transportation from its original place of harvest or collection to an intermediate point of conversion or usage. This implies the need for an improved and effective supply chain (Athanasios et al., 2009). However, for biomass integration in an existing ESC network to be worthwhile, the energy materials in use should be sourced locally because local sourcing of biomass materials can result to shorter supply chains with a higher predictability of delivery times and at reduced costs and GHG emissions. Moreover, different types of biomass resources, such as energy crops, agricultural residues, municipal solid waste (MSW) and forest residue make use of customized equipment for their collection, handling and storage, further increasing the level of complexity of the supply chain, which invariably is a determining factor in the investments and operational costs. This also affects the design and planning of the supply chain networks (Rentizelas et al. 2009). Therefore, to design an efficient biomass and ESC, the design in combination with adequate planning must be implemented with the material resources undergoing some conversion processes before the end products can be used effectively by consumers.

4.1 Proposed state task network (STN) approach

This study focuses on the CO_2 emissions mitigation potential of co-firing biomass with coal using a power plant model represented on the state-task network. Coal and biomass (wood chips) material resources are exploited locally through coal mining and biomass harvesting from trees. The mixed solid fuel is passed through a mechanical conversion process such as milling in order to reduce particle size, and ensure uniformity, thereby, resulting in an increased fuel surface area for co-firing operation. The biomass and coal mixture is passed through a conveyor and subsequently undergoes pneumatic transfer for onward delivery to either the co-combustion chamber or the co-gasification chamber. For the cost optimisation process, thermochemical conversion in the co-combustion chamber is preferred as it is less expensive than the gasification option. Co-combustion, which is also a more mature technology, negates the need for the pressure vessels required in the gasification option, thereby improving the overall process reliability of the power plant.

Moreover, t

he unique characteristic of the state-task network approach is that it consists of two types of nodes. The state nodes, which denote the feedstock, intermediate and final product, that are represented by circles while the processing operations nodes denote processes that transform energy materials from one or more input/initial states to one or more output/final states and are represented by rectangles as shown in Figure 4-1. These states and tasks nodes are linked by arcs and represent flow of materials from one point to another, as such, process operations are distinguished from the resources that are used in performing them.

Furthermore, the costs considered in the energy supply chain networks refer to absolute costs and not unit costs. However, in this particular case study, time value of money (net present value analysis) was not a considered objective function, and as such, the cost results are not discounted. In view of the aforementioned, the equations are formulated using the (MILP) method and same implemented and solved using the CPLEX 12 optimization solver of the General Algebraic Modelling System (GAMS) software, on an Intel® Core^{TM} i5-6200U CPU @ 2.40 GHz system with a zero optimality gap and under a negligible computational time. The limitations of the considered approach include no consideration of the solid fuel characteristics, such as particle shape, size distribution, composition, that would affect the quantity of biomass that could be co-fired with the coal. However, this work focused on the optimisation of the ESC from the technology cost and CO_2 emissions perspective to determine optimum fraction of biomass technologies in the ESC. Moreover, seasonality of biomass supply and technical challenges of its implementation in co-fired systems, such as slagging, fouling and corrosion, were not considered (IEA-ETSAP and IRENA, 2013). Finally, the model presented in this work follows the deterministic approach of modelling the ESC networks.

4.2 Modelling Approach

The model used in this work considers processes involved in the integration of biomass into an existing coal-fired ESC network leading to complexity of the ESC. In view of this development, the modelling approach of energy state task network (E-STN) formulation for supply chains introduced by Kondili et al. (1993) and applied by Zulkafli & Kopanos. (2018) has been adapted.

The formulation follows a multi-period timespan (20 equally distributed yearly time horizons), with the advantage of representing the problem as a state-task network (STN) model to allow for its extension to industrial supply chains with other systems. Long time horizons for decision making have been considered as this is usually necessary for design problems due to strategic decisions that need to be made. Moreover, the annual time periods considered can also be represented as monthly time periods, allowing a more flexible energy supply chain networks.

In the approach, material resources, individual tasks and useful products states are represented as separate nodes of the ESC network. In general, the E-STN comprise of two types of nodes: the state nodes denoted by circles which represent the feeds, intermediate and final products; and the task nodes denoted by rectangles, representing processing operations that transform materials from one or more input states to one or more output states as shown in Figure 1. These states and tasks nodes are linked by arcs, representing the flow of materials from one point to another.

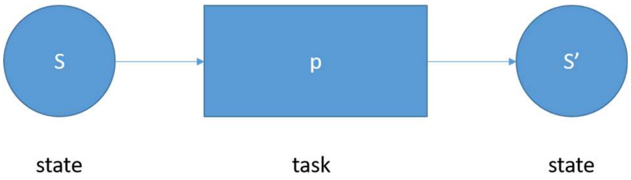


Figure 4-1 General representation of state-task network (STN)

For some of the constraints, such as capacity levels of technologies, the modelling framework considers bounds to account for the economies of scale on the lower side and biodiversity on the upper side (Babazadeh, 2016).

Establishment of technologies and bounds on expansion capacities are considered under the design constraints, while the availability of raw materials states and states connection with their balances are considered under the planning constraints. The link between design and planning are connected by constraints which provide bounds (upper and lower) on the level of operation on the amount of states converted, pre-processed or transferred by associated tasks with the use of applicable technology from one region to another in the time period under consideration.

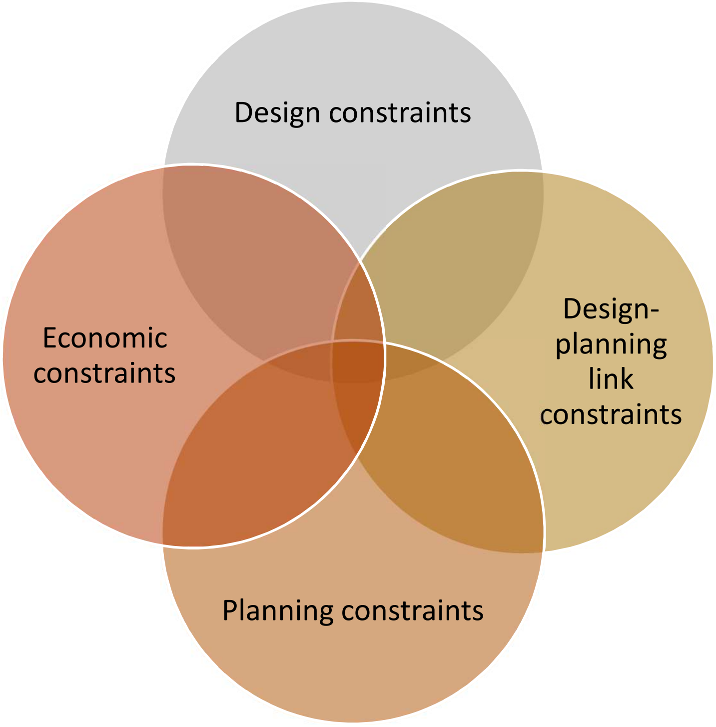


Figure 4-2 Major constraints for the proposed approach

The economics constraints relate to the overall costs considered in the ESC network. It consists of the fixed assets costs for conversion, coal/biomass exploitation and storage technologies that relate to the investment made in the establishment and expansion of technologies. Moreover, the total investment for establishing a transfer network between the two regions is represented by the fixed transfer costs. The fixed operating costs are the cost associated with maintenance and administration of the co-fired CHP plant on a day-to-day basis.

4.3 Optimisation Framework

4.3.1 Constraints for the design: Technologies establishment and corresponding expansions for installed capacities

The following binary variables are used in the modelling of technology establishment operations of the ESC networks:

$V_{(r,q,t)}$	=1, if coal/biomass exploitation, pre-processing and conversion technologies are established for the first time in region *r* at time period *t*, zero if otherwise.
$V^{G}{}_{(r,s,q,t)}$	=1, if storage technology *q* for state *s* is established for the first time in region *r* at time period *t*, zero if otherwise.
$Z_{(r,q,t)}$	=1, if capacity of coal/biomass exploitation, pre-processing and conversion technology q begins installing in region *r* at time period *t*, zero if otherwise.
$Z^{G}{}_{(r,s,q,t)}$	=1, if capacity of storage technology q for state *s* begins installing in region *r* in time period *t*, zero if otherwise.
$Z^{TR}{}_{(r,r',q,t)}$	=1, if capacity of transfer technology *q* starts installing in region *r* in time period *t,* zero if otherwise.

Equation (4-1) shows the initial installation of local/biomass exploitation or conversion ($V_{(r,q,t)}$) and storage technology, ($V^{G}{}_{(r,s,q,t)}$) , in region *r* and at time period *t*, with the constraint showing that it can happen at most once in the internal region, while Equations (4-2) and (4-3) depict the link in binary variables for local/biomass exploitation, conversion and storage technologies. It is important to note that the establishment of these technologies cannot exceed the corresponding capacities, as shown in Equations (4-1–4-3).

$$\begin{aligned} &\sum_{t\in T} V_{(r,q,t)} \leq 1 \quad \forall r \in R^{in}, q \in Q_r^{PRC} \\ &\sum_{t\in T} V^{G}_{(r,s,\mathrm{q},t)} \leq 1 \quad \forall r \in R^{in}, s \in S, q \in Q^{G}_{(s,r)} \end{aligned} \qquad \textbf{(4-1)}$$

$$\begin{aligned} &V_{(r,q,t)} \le Z_{(r,q,t)} \qquad \forall r \in R^{in}, q \in Q_r^{PRC}, t \in T \\ &V^G_{(r,s,q,t)} \le Z^G_{(r,s,q,t)} \quad \forall r \in R^{in}, s \in S, q \in Q^G_{(s,r)}, t \in T \end{aligned} \tag{4-2}$$

$$\begin{aligned} &V_{(r,q,t)} \ge Z_{(r,q,t)} - \sum_{t'<t} V_{(r,q,t')} \qquad \forall r \in R^{in}, q \in Q_r^{PRC}, t \in T \\ &V^G_{(r,s,q,t)} \ge Z^G_{(r,s,q,t)} - \sum_{t'<t} V_{(r,s,q,t')} \quad \forall r \in R^{in}, s \in S_r^{\;G}, q \in Q^G_{(s,r)}, t \in T \end{aligned} \tag{4-3}$$

4.3.2 Overall capacity for technologies establishment and expansions

The total installed capacity for each region and time period, for conversion or biomass/local exploitation technology, ($C_{(r,q,t)}$), storage technology, ($C^G{}_{(r,s,q,t)}$) and transfer technology, ($C^{TR}_{(r,r',q,t)}$) with their expansions are represented by Equations (4-4), (4-5) and (4-6), respectively. The initially established capacities for exploitation/conversion, storage and transfer technologies are represented respectively by the parameters, $\varphi, \varphi^G, \varphi^{TR}$, while E, E^G, E^{TR} denote the expansions in capacities happening at every applicable time period and region.

As shown in Equation (4-6), there is no existing transfer station representing the total installed capacity for transfer technology for each region and time period in addition to their expansions $C^{TR}_{(r,r',q,t-1)}$ at time t=1. As it is a first time period (t=1), it is assumed that the production of transferrable states must first occur in this time period (t=1) before the transfer technologies can be established at the time periods $t > 1$. It is assumed that for an additional technology to be established, a capacity expansion on the applicable technologies must occur at the same time with establishing the technologies.

$$\begin{aligned} &C_{(r,q,t)} = \varphi_{(r,q)} + C_{(r,q,t-1)} + E_{(r,q,t)} \forall r \in R^{in}, q \in Q_r^{\;CPR}{}_{(s,r)}, t \in T : t = 1 \\ &C_{(r,q,t)} = C_{(r,q,t-1)} + E_{(r,q,t)} \forall r \in R^{in}, q \in Q_r^{\;CPR}, T : t > 1 \end{aligned} \tag{4-4}$$

$$\begin{aligned} &C^{G}{}_{(r,\mathrm{s},q,t)} = \varphi^{G}{}_{(r,\mathrm{s},q)} + C^{G}_{(r,\mathrm{s},q,t-1)} + E^{G}_{(r,\mathrm{s},q,t)} \forall r \in R^{in}, \mathrm{s} \in \mathrm{S}_{r}{}^{G}\ q \in Q^{G}{}_{(s,r)}, t \in T : t = 1 \\ &C^{G}{}_{(r,\mathrm{s},q,t)} = C^{G}{}_{(r,\mathrm{s},q,t-1)} + E^{G}{}_{(r,\mathrm{s},q,t)} \forall r \in R^{in}, \mathrm{s} \in \mathrm{S}^{G}{}_{r}, q \in Q^{G}{}_{(s,r)}, T : t > 1 \end{aligned} \tag{4-5}$$

$$\begin{aligned} &C^{TR}_{(r,r',q,t)} = \varphi^{TR}_{(r,r',j)} + E^{TR}_{(r,r',q,t)} \qquad \forall r \in R^{in}, r' \in R^{TR}_{r'}, q \in Q^{TR}_{(r,r')}, t \in T : t = 1 \\ &C^{TR}_{(r,r',q,t)} = C^{TR}_{(r,r',q,t-1)} + E^{TR}_{(r,r',q,t)} \qquad \forall r \in R^{in}, r' \in R^{TR}_{r'}, q \in Q^{TR}_{(r,r')}, t \in T : t > 1 \end{aligned} \tag{4-6}$$

Equations (4-7) and (4-8) are used to determine the gamma (γ) parameters that represent the bounds (upper and lower) on allowable expansion levels of associated technologies of the supply chain. Also, parameters $\mu_{(r,q,t)}$ and $\mu_{(r,r',q,t)}$ are the time for installation of a technology's expansion in capacity after it is available and time for installation for a transfer technology that connects the two regions for an implementation start in the period under consideration respectively.

$$\begin{aligned} &\gamma^{\min}_{(\mathrm{r,q},t)} Z_{(\mathrm{r,q},t-\mu_{(\mathrm{r,q},t)})} \le E_{(\mathrm{r,q},t)} \le \gamma^{\max}_{(\mathrm{r,q},t)} Z_{(\mathrm{r,q},t-\mu_{(\mathrm{r,q},t)})} \qquad \forall r \in R^{in}, \mathrm{q} \in Q^{CPR}_{r}, t \in T \\ &\gamma^{\min}_{(z,j,t)} Z^{G}_{(\mathrm{r},s,\mathrm{q},t-\mu_{(\mathrm{r,q},t)})} \le E^{G}_{(\mathrm{r},s,\mathrm{q},t)} \le \gamma^{\max}_{(\mathrm{r,q},t)} Z^{G}_{(\mathrm{r},s,\mathrm{q},t-\mu_{(\mathrm{r,q},t)})} \quad \forall r \in R^{in}, s \in S^{G}_{r}, \mathrm{q} \in Q^{G}_{(s,\mathrm{r})}, t \in T \end{aligned} \tag{4-7}$$

$$\gamma^{\mathrm{TR,min}}_{(\mathrm{r,r'},t)} Z^{TR}_{(\mathrm{r,r',q},t-\mu^{TR}_{(\mathrm{r,r',q},t)})} \le E^{TR}_{(\mathrm{r,r',q},t)} \le \gamma^{\mathrm{TR,max}}_{(\mathrm{r,r'},t)} Z^{TR}_{(\mathrm{r,r'},j,t-\mu^{TR}_{(\mathrm{r,r',q},t)})} \qquad \forall r \in R^{in}, \mathrm{r'} \in R^{TR}_{r'}, \mathrm{q} \in Q^{TR}_{(\mathrm{r,r'})}, t \in T \tag{4-8}$$

4.3.3 Availability for raw materials states

The raw materials considered in this work is wood chips, which is a type of biomass and a good-quality fuel that requires a simplified harvesting and drying (Warren et al., 1995) and a non-intermittent renewable energy source, in addition to coal, both are solid fuels. The capacity of inventory for the selected technology is denoted by Equation (4-9), which indicates that the amount of renewable state consumed by task $p \in P$ brought about by biomass/coal exploitation technologies $q \in Q$, ($M_{(r,r,p,q,t)}$) in addition to those transferred to other regions, ($M_{(r,r',p,q,t)}$) cannot exceed the maximum amount of the state that is available originally at the source region, ($\omega_{(r,s,t)}$).

$$\sum_{p \in P_s^{RM}} \sum_{q \in (Q_r^E \cap Qp)} M_{(r,r,p,q,t)} + \sum_{p \in P_s^T} \sum_{q \in (Q_{(r,r')}^T \cap Q_p)} \sum_{r' \in R_{r'}^T} M_{(r,r',p,q,t)} \leq \omega_{(r,s,t)} \quad \forall r \in R, s \in S_r^{RM} : s \notin S^{NR}, t \in T \qquad \textbf{(4-9)}$$

4.3.4 Connection and balance for applicable states

Equation (4-10) shows the link between connection and balance in each of the regions at the end of each time period. This equation shows that the level of inventory of storable states $s \in S_r{}^G$ at the end of each time period and region depend on the following:

(i) The inventory at the end of the time period before the one being considered, given by $G_{(r,s,t-1)}$ with consideration given to associated deterioration, $\eta_{(r,s,t)}$. In the case of biomass, if the moisture content is not properly reduced before storage, fungi, which can destroy wood by metabolizing cellulose, hemicellulose and lignin are able to cause material losses;

(ii) The applicable demand for the state;

(iii) No sales or unmet demands;

(iv) Quantity of states disposed;

(v) Produced amount from local/biomass exploitation task;

(vi) Quantity of transferred states either through the inlet or outlet processes; and

(vii) Tasks produced, $P \in P_s{}^+$ or consumed $P \in P_s{}^-$ by other tasks.

For states that cannot be stored, $s \notin S_r{}^G$ all the criteria listed above apply except from the first one.

$$
\begin{aligned}
G_{(z,s,t)} = {} & (1-\eta_{(z,s,t)})G_{(z,s,t-1)} - \zeta_{(z,s,t)} + N_{(z,s,t)} - D_{(z,s,t)} + \overbrace{\sum_{p\in P_s^{RM}} \sum_{q\in(Q_r^E \cap Qp)} M_{(r,r,p,q,t)}} \\
& + \overbrace{\sum_{r'\in R_{r'}^{TR}} \sum_{p\in P_s^{TR}} \sum_{q\in(Q_{(r',r)}^{TR} \cap Qp)} \kappa_{(s,p,q)}^{+} M_{(r',r,p,q,t)}} - \overbrace{\sum_{r'\in R_{r'}^{TR}} \sum_{p\in P_s^{TR}} \sum_{q\in(Q_{(r,r')}^{TR} \cap Qp)} \kappa_{(s,p,q)}^{-} M_{(r,r',p,q,t)}} \\
& + \overbrace{\sum_{p\in P_s^{+}} \sum_{q\in(Q_r^C \cap Qp)} \kappa_{(s,p,q)}^{+} M_{(r,r,p,q,t)}} - \overbrace{\sum_{p\in P_s^{-}} \sum_{q\in(Q_r^C \cap Qp)} \kappa_{(s,p,q)}^{-} M_{(r,r,p,q,t)}} \quad \forall r\in R, s\in S_r, t\in T
\end{aligned}
$$

$$
\begin{aligned}
& G_{(r,s,t=0)} = G_{(z,s)}^{0} && \forall r\in R, s\in S_r^G \\
& G_{(r,s,t)} = 0 && \forall r\in R, s\notin S_r^G, t\in T \\
& D_{(r,s,t)} = 0 && \forall r\in R, s\notin S_r^D, t\in T
\end{aligned}
$$

(4-10)

Biomass inventory, $G^0_{(r,s)}$ considered as the initially available inventory of state *s* in region *r* (at the initial time period, *t=0*) and has been set to 10,000 units. It is worth noting that the model presented does not depend on units used as long as the units are consistent. The main focus of this study is to show new models that can solve the kind of case study presented.

4.3.5 Objective function

The objective function is set to achieve minimisation of overall costs that comprise the fixed assets costs for technologies (pre-processing and conversion, biomass/local exploitation and storage) that have been installed, fixed assets cost for transfer technology, and the fixed and variable operating costs. The variable cost is made up of cost of production, inventory cost, transfer cost and raw materials cost.

$$\min \sum (FAC_t + FAC_t^{TR} + FOC_t + VOC_t) \tag{4-11}$$

In Equation (4-11), FAC_t is the fixed assets costs associated with biomass/local exploitation, conversion, pre-processing and storage technologies in time period *t*, FAC_t^{TR} is that of the transfer technologies also in time period t, FOC_t is the fixed operating costs in time period t, while, VOC_t is the variable operating cost in time period *t* and are shown by Equations (4-12–4-15), respectively.

$$FAC_t = \sum_{r \in R^{in}} \sum_{q \in Q_r^{PRC}} (\varepsilon^0_{(r,q,t)} V_{(r,q,t)} + \varepsilon_{(r,q,t)} E_{(r,q,t)}) + \sum_{r \in R^{in}} \sum_{s \in S_r^{\ G}} \sum_{q \in Q^G_{(s,r)}} (\varepsilon^0_{(r,q,t)} V^G_{(r,s,q,t)} + \varepsilon_{(r,q,t)} E^G_{(r,s,q,t)}) \quad \forall t \in T \qquad \textbf{(4-12)}$$

$$FAC_t^{TR} = \sum_{r \in R^{in}} \sum_{r' \in R_{r'}^{TR}} \sum_{q \in Q^{TR}_{(r',r)}} (\varepsilon^{TR0}_{(r,r'q,t)} Z^{TR}_{(r,r',q,t)} + \varepsilon^{TR}_{(r,r',q,t)} E^{TR}_{(r,r',q,t)}) \quad \forall t \in T \qquad \textbf{(4-13)}$$

$$FOC_t = \sum_{r \in R^{in}} \sum_{q \in Q_r^{PRC}} \delta_{(r,q,t)} C_{(r,q,t)} \quad \forall t \in T \qquad \textbf{(4-14)}$$

$$VOC_t = CM_t + HC_t + IC_t - TRC_t + DC_t \ + NS_t \quad \forall t \in T \qquad \textbf{(4-15)}$$

The variable operating cost is a combination of raw materials costs (CM$_t$), cost for the production of useful product state (HC$_t$), inventory cost (IC$_t$), transfer costs between regions (TRC$_t$), penalty for disposal of unwanted state to the environment (DC$_t$), cost for unmet demands (NS$_t$), which are represented by Equations (16–21), respectively.

$$CM_t = \sum_{r \in R^{in}} \sum_{s \in S_r^F} \sum_{p \in P_s^F} \sum_{q \in (Q_r^E \cap Q_s \cap Qp)} \psi_{(r,s,p,q,t)} M_{(r,r,p,q,t)} \quad \forall t \in T \qquad \textbf{(4-16)}$$

$$HC_t = \sum_{r \in R^{in}} \sum_{s \in S_r} \sum_{p \in P_s^+} \sum_{q \in (Q_z^{PRC} \cap Q_p)} \pi_{(r,s,p,q,t)} M_{(r,r',p,q,t)} \quad \forall t \in T \qquad \textbf{(4-17)}$$

$$IC_t = \sum_{r \in R^{in}} \sum_{s \in S^G{}_r} \lambda_{(r,s,t)} G_{(r,s,t)} \quad \forall t \in T \qquad \textbf{(4-18)}$$

$$TRC_t = \sum_{r' \in R_r} \sum_{\in R_{r'}^{TR}} \sum_{s \in (Sr \cap Sr')} \sum_{p \in P_s^{TR}} \sum_{q \in (Q^{TR}_{(r',r)} \cap Qp)} \vartheta_{(r',r,s,p,q,t)} M_{(r',r,p,q,t)} \quad \forall t \in T \qquad \textbf{(4-19)}$$

$$DC_t = \sum_{r \in R^{in}} \sum_{s \in S_r^D} \lambda^D_{(r,s,t)} D_{(r,s,t)} \quad \forall t \in T \tag{4-20}$$

$$NS_{(t)} = \sum \sum \lambda^N{}_{(r,s,t)} N_{(r,s,t)} \forall t \in T \tag{4-21}$$

4.4 Description of the case study

The considered ESC consists of eight states (*s1–s8*), where *(s*1, *s*8) denote the raw material state, which are coal *(s1*) and biomass (woodchips,*s8*) . (*s2*, *s3, s6*) represent energy material resources, which are obtained after the combination of *s*1 and *s8* have undergone both mechanical (milling) and thermochemical conversion, moreover, these states are tangible and as such are storable. Wood chips have been selected as a source of biomass as these are frequently considered for co-firing with coal to achieve a reduction in CO_2 emissions. Commonly, 1-10% biomass is co-fired in coal-fired power plants in these instances (IEA-ETSAP and IRENA, 2013). Biu et al. (2018) stated that co-firing biomass led to an increase both in quality and quantity of waste heat recovered from exhaust gases, which invariably is one of the avenues for the improvement of energy efficiency in bioenergy and carbon capture and storage (BECCS) system. Furthermore, they stated that there was an appreciable reduction in SO_x emissions when there was an increment in co-firing ratio of biomass as well as when coal with low sulphur content was used. Additionally, Furubayashi and Nakata (2018) optimised the renewable material and transportation pathways for biomass using the Geographic Information System in Tohoku region (Japan). They reported the smallest energy consumption (3.8 GJ/t), lowest supply cost (1558 JPY/GJ) and largest CO_2 reduction (252 ktCO_2/y) in case of woodchips, in comparison to wood pellets and torrefied pellets.

A direct method of co-firing biomass with coal in the combustion chamber of the boiler is assumed in the model. In essence, for a greater level of simplicity and cost effectiveness of the process in a pulverised coal and biomass co-fired CHP plant, biomass and coal could be mixed on the coal conveyor belt and the mixture subsequently fed into the boiler (Zafar, 2019). Furthermore, (*s5, s7*) are the states representing energy forms that are either heat, electricity or both and cannot be stored. The unwanted substance state, which is also a pollutant, is represented by state (*s4*).

Additionally, the considered ESC includes seven tasks (*p1–p7*) that are described as exploitation tasks (*p1, p7)*, conversion tasks (*p2, p4, p5*) and transfer tasks (*p3, p6*). Also, the ESC comprises eleven technologies that are associated with each task denoted by (*q1–q11*). Technologies (*q1,q10*) are exploitation technologies, (*q2, q5, q6, q7, q8)* are conversion technologies, (q3, q4, q9) are the transfer technologies and (q11) represents the storage technology. The storage technologies are also associated with the raw materials and energy material resources states given by (*q-s01,q-s08, q-s02_1, q-s02_2, q-s03, q-s06*).

There are 20 equally distributed yearly time horizons and the tasks take place in three regions, of which two (*r1, r2*) are internal regions, while the third (r3) is an external region. The conversion task *(p2)* represents milling operation, a type of mechanical process that is carried out on both biomass and coal, while (*p4*) can either be combustion or gasification, which is one of the processes for thermochemical conversion of biomass and coal. A study on gasification involves the conversion of biomass into syngas, which is a primary/intermediate product and a mixture of H_2 and CO which are predominant amongst all other products obtained. Furthermore, the secondary products could be upgraded bio-syngas (with an adjusted H_2/CO ratio), ethanol with C_3-C_4 alcohols, methanol, gasoline, formaldehyde and di-methyl ether (DME). The bio-syngas obtained can then be used in a gas engine for the production of electricity and heat. But in this case study, the combustion process is preferred due to its cheaper and more mature technological nature.

Importantly, biogenic carbon (C), which is the emissions related to the natural carbon cycle, as well as those resulting from the combustion, harvesting, digestion and fermentation, decomposition or processing of biologically based materials have not been considered in this case study. Biomass (woodchips) that has been considered is assumed to be sourced locally and sustainably, and as such, its combustion is considered to be carbon neutral. Additionally, Biu et al.

(2018) highlighted that if CO_2 from biomass combustion is captured and permanently stored, considering that biomass is sustainably sourced, the considered BECCS systems can become carbon negative.

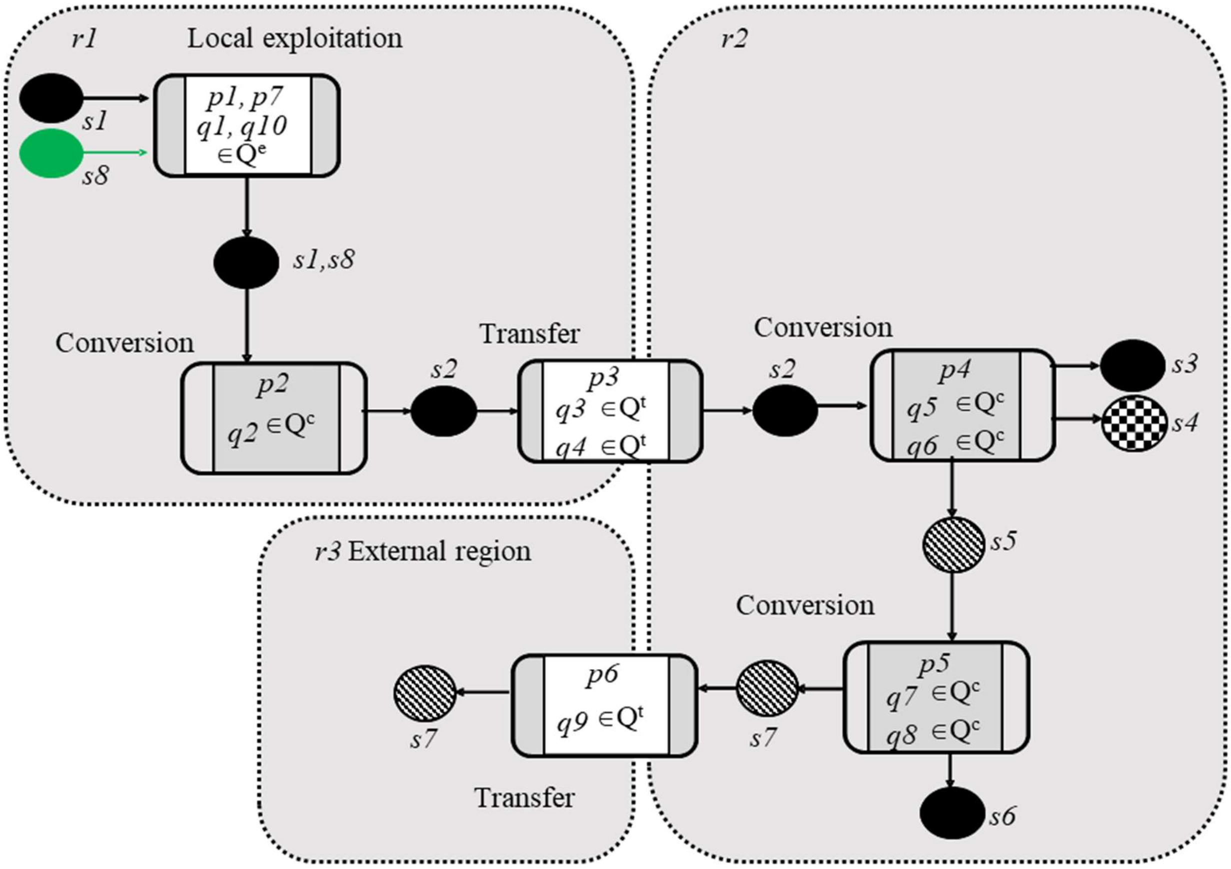


Figure 4-3: Illustrative energy state-task network for energy supply chain network

The raw material states, *s1* and *s8* and the energy material resources states, (*s2, s3, s6)* can be stored , while the energy form states, (*s5 and s7*) cannot be stored. Importantly, the undesired substance (*s4*) would not be stored.as indicated in Table 4-1.

It is worth noting that the model presented is a generalized model that does not depend on the biomass type and properties. The data for technology cost and CO2 emissions were selected for wood chips as the source of biomass, mostly because it is commonly considered for co-firing with coal. Therefore, the model prediction should be valid for biomass with relatively low moisture content.

Table 4-1 Storage technologies available per state and region

States that are storable (s)	Internal region (r1)	Internal region (r2)
s1	qs1	
s2	qs2	qs2
s3	-	qs3
s6	-	qs6
s8	qs8	-

Table 4-2: Minimum (γmin) and maximum (γmax) capacity expansion level of associated technology, fixed operating cost for total installed technology (δ), costs associated with states production through conversion technologies (π), Zulkafli and Kopanos, (2018a), investment cost for technology establishment (ε^0) and cost required to increase the capacity of a technology (ε)

Technology	γ^{min}	γ^{max}	$\varepsilon^0_{(r,q,t)}$ (m.u./unit)	$\varepsilon_{(r,q,t)}$ (m.u./unit)	$\delta_{(r,q,t)}$ (m.u./unit)	$\pi_{(r,s,p,q,t)}$ (m.u./unit)
q1	5	50	(1,326-1,820)	(1,122-1,540)	-	-
q2	5	50	20,000	(1,800-2,000)	15	12
q3	0	30	1,000	(580-650)	0	0
q4	0	30	1,000	(550-650)	0	0
q5	10	40	28,000	(3,950-4,139)	20	20
q6	10	40	25,000	3,500	40	25
q7	5	30	20,000	3,000	30	30
q8	5	30	26,000	2,600	25	40
q9	0	50	8,000	800	0	0
q10	5	50	(1,458.6-2,002)	(1,122-1,540)	-	-

From Table 4-2, parameter values for the bounds on the capacity expansions levels (in relative units) for local exploitation *(q1,q10),* conversion (*q2,q5,q6,q7,q8*) and transfer technologies *(q3,q4,q9*), denoted by γ^{min} and γ^{max} , fixed operating cost for the total installed capacity of technology q (δ) and those associated with states production through conversion technologies (π), were obtained from Zulkafli & Kopanos (2018a), while the values of investment cost for technology establishment (ε^0) and that required to increase the capacity of a technology (ε), were obtained as solution from the model formulation.

4.5 Results, analysis and discussion on integrating biomass into energy supply chain networks[1]

The normalised demand profile graph Figure 4-4 was plotted by using the maximum demand for useful/final products over the entire planning horizon of each state (*s*) and region (*r*) as a baseline for total demands made in each time period. From the energy resource produced in the internal region (*r2.s3)* there was no demand in the first time period (*t1*) . *s*3 could be biomass and coal co-firing residues, such as fly/flue ash, while *s*6 could be bottom ash. However, if gasification is considered , the syngas produced, which is an intermediate product and a mixture of CO and H_2 will undergo further treatment to convert it into upgraded bio syngas, in order to obtain a secondary product with an adjusted CO/H_2 ratio for direct use in boilers and gas turbines. Additionally, it could act as a precursor for the synthesis of a large range of other chemicals (Zafar, 2018). Also, for energy resource (*s6*), which is bottom ash, there was no demand in the first time period (*t1*). However, the maximum demand for *s6* was predicted at the time period *t13,* with a value of 106 relative units (ru) that is equivalent to 1 ru in the normalised demand profile graph. However, with consideration given to co-combustion of coal and biomass in the combustion chamber, the result is the production of secondary energy material resources, which could be coal and biomass residue(*s3*), energy form state (*s*5) in the form of heat, as well as unwanted substances (s4) in form of CO_2, NO_x, SO_2 in addition to varying and naturally occurring radioactive materials. It is worth noting that, *s3*, which is biomass and coal co-firing residues, such as fly ash or flue ash and *s6*, which can be said to be bottom ash is combustion residue that is non-combustible in a power plant, however, both fly ash and bottom ash make up coal ash.

Moreover,fly ashes from combustion can be utilized beneficially as replacement of pozzolans in cements (Eijk et al., 2012), and also for Portland cement concrete (PCC) pavement and bottom ash can be use in place of sand for road construction.

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[1] Manuscript description on integrating biomass into ESC networks, Jounal of Cleaner Production (2019) (Avaailable online).

Further, the produced heat of combustion is used to convert water into steam, which drives the turbine to produce electricity in the generator. The produced electrical power and heat (*s7)*, which are energy form states, are obtained from the turbine with their production rates depending on the amount of steam produced by steam boiler which enters the turbine. Electricity is subsequently transferred to various points of usage, while heat can be used in process or district heating. Furthermore, the results presented in Figure 4-4 show that energy form state *s7* in region *r2* (*r2.s7*)*,* which represents electricity, had the highest demand in time period *t14* with a value of 106 ru*.* From the trend shown in Figure 4-4, higher demands for products occurred at later time periods, between *t13 and t20*, and could be attributed to the production of useful products states at those times*.* However, energy resource state *s7* in region *r3* (*r3.*s7) predicted its highest demand at the last time period (*t20*). This occurred as a result of transfer of energy form state *s7* from an internal region *r2* to an external region *r3*. Finally, the scenario predicted at this state and region confirmed the non-availability of associated inventory.

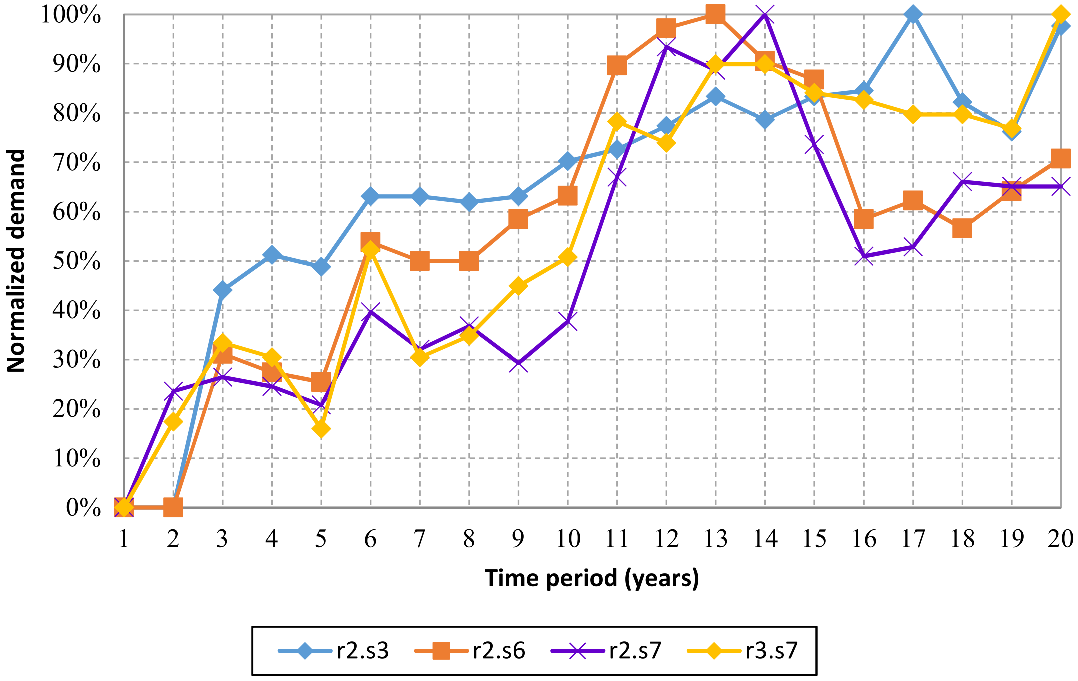


Figure 4-4 Normalized demand profile graph for energy resource produced in both internal regions (*r2.s3, r2.s6, r2.s7*) and external region (*r3.s7*)

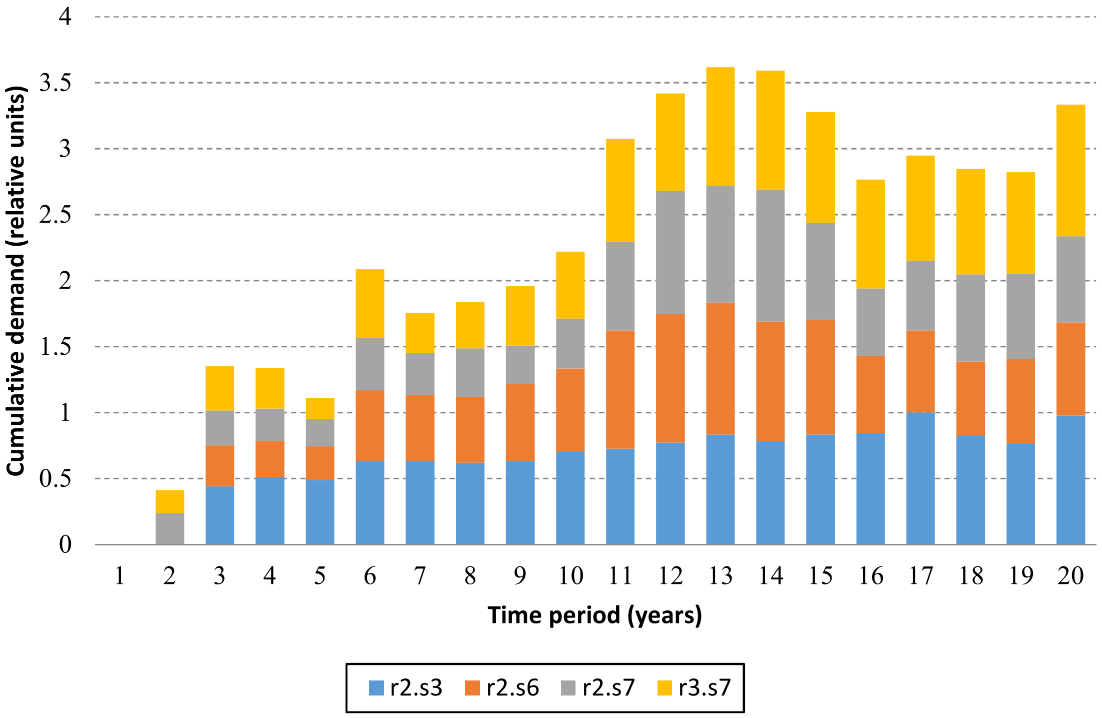


Figure 4-5 Cumulative demand graph for states (*s*) in regions (*r*) obtained by dividing the individual demand at every time period by the maximum value at each state and region.

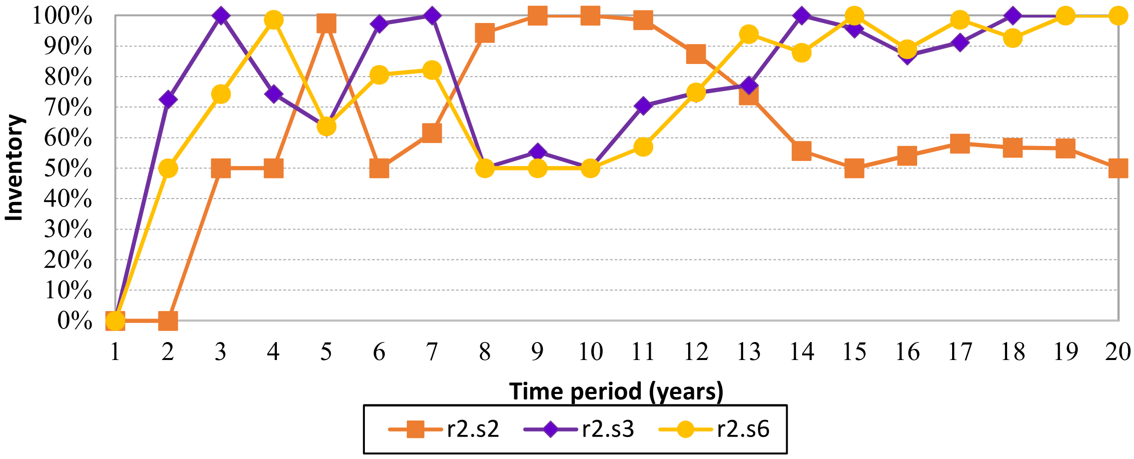


Figure 4-6 Inventory profile graph for energy material resource states *(s)* that can be stored in regions (*r)* where applicable.

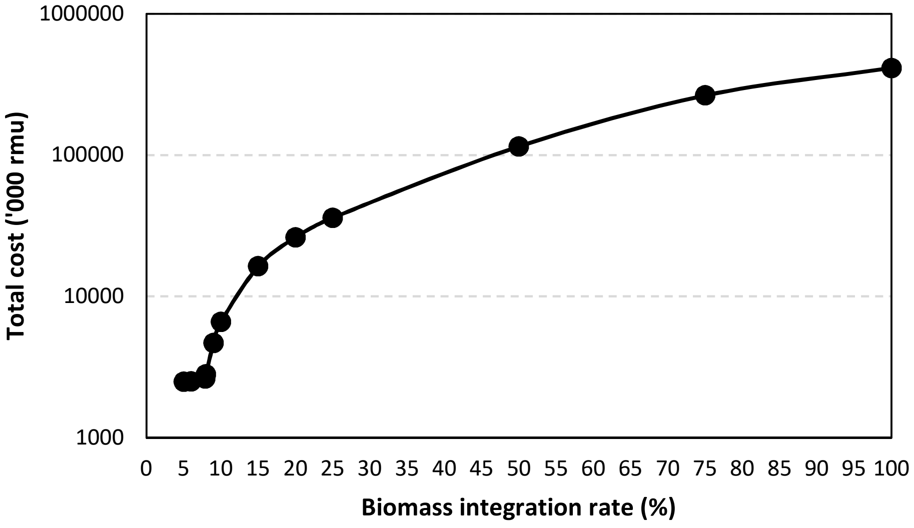


Figure 4-7 Effect of biomass fraction in the mixed solid fuel on the total cost of energy supply chain network

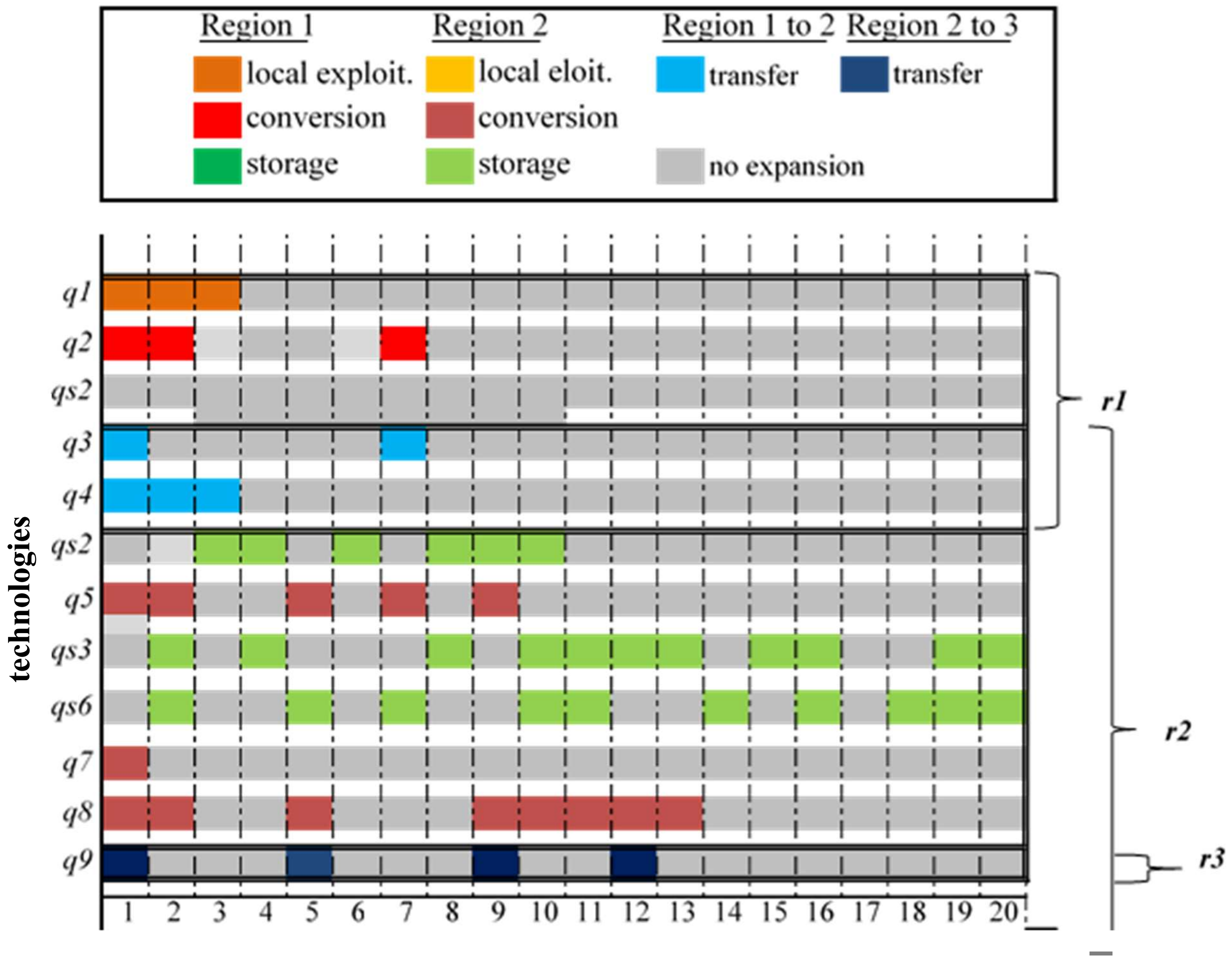
The optimal solution of 2,515,206 relative money units (rmu), representing the overall cost of the ESC was obtained by solving the mixed integer linear programming (MILP) model for only coal-fired power plant. This was obtained using the CPLEX 12 optimisation solver of the General Algebraic Modelling System (GAMS), on an Intel (R) core ^{TM} i5-6200U CPU @ 2.40GHz system with a zero optimality gap and under a negligible computational time. However, under same modelling but with slightly modified optimisation conditions, the co-fired CHP plant utilizing biomass and coal as energy material resources returned a value of 2,630,260 rmu.

Integration of 7.9% of biomass material resource suggested the potential of a 4.32% decrement in the emissions level of the considered ESC network. In as much as increased biomass fraction in the mixed solid fuel in the ESC resulted in a substantial reduction in emissions level, at above 9% of biomass in the ESC, a sharp increase in the overall cost (Figure 4-7) of the ESC network was observed, this is due to the fact that operating costs in power plants are much higher for biomass in comparison to coal, which is as a result of an increased in the technology cost of collection,pre-processing, as a result of increased moisture content transportation, preparation , on-site handling and delivery of the fuel.

Therefore, biomass co-firing with coal was not economically justifiable at that point. Importantly, at the biomass fractions in the mixed solid fuel of 5–6% (2,495,058–2,503,809 rmu), the total cost of the ESC network was marginally lower than that of the ESC network without biomass integration (2,515,206 rmu). The total cost of ESC network at the biomass fractions of 8% was shown to increase to 2,811,267 rmu, a substantial increase from 2,630,260 rmu at 7.9%. Importantly, this is in line with the maximum biomass fraction of 10% reported by Knapp et al. (2019). Therefore, the latter has been used in further analysis. Overall, such variation in the total cost of the ESC network with biomass fraction can be associated to subsequent reduction of the cost associated with emissions in the ESC network, as biomass, which is considered a carbon neutral energy material resource, is assumed to have been sourced locally and sustainably. As a result, its conversion process is associated with less CO_2 emissions compared to that of coal. Moreover, biomass co-firing is capable of reducing the nitrogen oxides (NO_x) as well as sulphur oxides (SO_x) that are released during thermochemical conversion of coal. Yet, at higher biomass fractions, the cost associated with its transportation and losses during transportation resulted in increased total cost of the ESC network.

Figure 4-5 shows the total demand for states (s) in regions (r) that apply to them. *s3* and *s6* are storable energy material resources obtainable in region *r2* , while *s7* represents an energy form state, which is in demand and not stored, thereby necessitating its transfer from internal region *r2* to external region *r3*. Figure 4-5 reveals that the highest cumulative demand for useful products states was obtained in time period *t13* with a value of 3.62 relative units. For storable energy materials with high demands, storage level for storable products will be low and vice-versa as shown in the inventory profile graph (Figure 4-6).

The Gantt chart shown in Figure 4-8 depicts the ideal planning for capacity expansion in the considered planning horizon (binary variables, Z, Z^{TR}, Z^{G}). In the planning, local exploitation (*q1, q10*), conversion (*q2, q5, q6, q7, q8*), transfer (*q3, q4, q9*) and storage technologies (*qs2, qs3, qs6*) are all considered. Furthermore, in Figure 4-8, all local exploitation, conversion and transfer technologies were established in the first time period as there was no consideration for their initial installation, the only exception to this is storage technology which is not established until there has been production of storable states. There was no storage in region *r1*, but exploitation, conversion and transfer technologies were evident as demand for these states occurred from the second time period onwards. Additionally, the results revealed that the cost of establishing these technologies was lower in the first time period, compared to subsequent time periods. This, however, can be attributed to the amount of states produced in the considered time periods. It is important to highlight that the storage technologies were established in region *r2*, following the production of storable states. Capacity expansions occurred in the early time periods, for example, conversion capacity expansions occurred from time period 1 to time period 13. This can be attributed to the fact that the cost of increasing the capacities of available technology was lower in the earlier time periods than in the later time periods, which may have arisen from the need for the increased size of technology to meet the increase in demand. Importantly, the results show that the latest time period for the establishment of the transfer technology *q9* was at time period 12, as the investment cost for the increment of transfer technology ($\varepsilon_{(r,q,t)}$) started to increase from time period 14. Also, there was no establishment of storage technologies in region 1, as shown in the Gantt chart. With the establishment of technologies in time period 1, the storage technology, *qs2*, which occurred in region 2, was first established in the time period 3 after there has been production of storable states, while storage technologies, *qs3* and *qs6* were first established in the time period 2. Additionally, there were capacity expansions for storage technologies *qs3* and *qs6* in latter time periods (*t19 and t20*) which was due to increased production of storable states.



Time periods (years)

Figure 4-8: Overall capacity expansion planning per associated technologies (*q*) in regions (*r*) and at time periods (*t*)

The representation of the costs components of the considered ESC network in Figure 4-9a and Figure 4-9b revealed the fixed assets cost had the most significant contribution to the total ESC network cost, with a value of 1,575,429 rmu, which is equivalent to about 60% of the overall cost of the ESC networks with biomass integration. This is only 0.35% higher compared to the fixed asset cost of the ESC network based on coal (1,569,934 rmu). Such a small increase in the fixed asset cost was obtained due to the assumption that biomass (wood chips) was co-fired directly in the existing coal-fired CHP plant using the same combustion chamber. It is worth noting that the fixed asset cost of the co-fired CHP plant comprises of the cost of land, equipment (combustion chamber, steam cycle), power house building, testing and commissioning. The variable costs for the ESC network with biomass was 455,964 rmu (17%), which was 25% higher compared to that of the ESC network based only on coal (364,576 rmu, 14%). This could be associated to a higher price and volume of biomass required to achieve the same energy output as the variable cost is a combination of raw materials, production, inventory, transfer and costs associated with disposal of states in the network. Furthermore, the costs of emissions and fixed transfer in the ESC network with biomass integration were estimated to be 291,727.7 rmu (11%) and 165,839.5 rmu (6%) respectively. The corresponding figures for the ESC network based only on coal were 304,895 rmu (12%) and 140,874 rmu (6%), respectively. This indicates that biomass integration into the ESC network can reduce the cost of emissions by 4.3%. Finally, the fixed operating cost was estimated to be 141,300 rmu (6%) and 134,928 rmu (5%) in the ESC with and without biomass integration, respectively. These results have revealed that technology establishment which falls under the fixed asset cost, amongst other criteria, demands proper optimisation as one of the means of further achieving a reduction in the overall cost of supply chain networks.

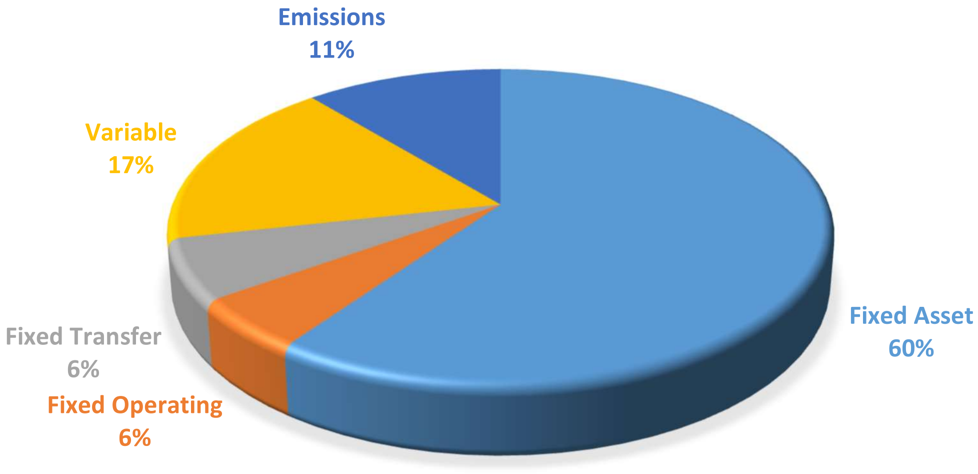


Figure 4-9a Total cost breakdown for ESC network with biomass integration

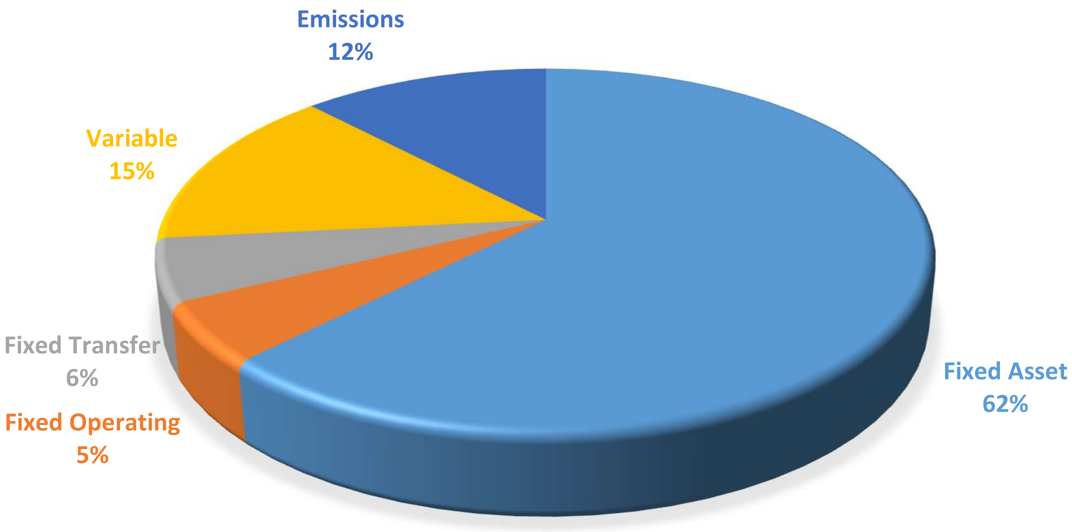


Figure 4-9b Total cost breakdown for ESC network without biomass integration (coal only)

5 METHODS FOR RESEARCH DATA COLLECTION

While research methods deal with strategies and techniques of data collection for revealing information or for an in-depth understanding of a topic, the processes of analysing collated data vary in numerous ways. Moreover, there are various types of research methods that are suitable for unique cases, also, some research methods or tools for collating research data may involve combination of different methods in order to achieve more accurate results (University of Newcastle Library guides, 2019). Furthermore, as a precautionary measure for safeguarding the rights of human subjects, approval was obtained from Cranfield University Research Ethics System (CURES) for the developed questions before same were disseminated to respondents (Appendix C.1).

5.1 Methodology for energy survey and analysis using qualtrics

The non-probability sampling method has been used in the survey and as such, the chosen samples are non-random. Non-random sampling method was employed as it has the advantage of being cheaper and essential for research based on formulation in addition to hypothesis generation, with its results providing astounding understanding into a given scenario. It should be noted that the choice of the utilized method is of importance because, the aim of conducting the survey is to propose strategies for improved renewables' embracement in the UK energy mix. Furthermore, the snowballing, also referred to as chain sampling, chain-referral sampling, or referral sampling, method of non-random sampling was used by the application of online survey-questionnaire mode of data collection. In essence, developed questionnaires were disseminated through emails and mobile phones and with the consideration that the sampling frame was not easy to identify. Instead, original subjects were sampled and the questionnaires were distributed further amongst their acquaintances for completion in accordance with the snowballing method of non-probability sampling with all responses analysed in an un-biased manner and conclusions drawn.

The sampling frame or elements are the units being analysed, which invariably represent a list of people who are part of the population of the elements being studied. It is worth noting that, the elements/ sampling frame may be human beings, but in some instances, they could represent schools, households or any other kind of elements, however in the conduct of this survey, the elements considered are individual persons. In essence, the choice of elements/ sampling frame are intentional, making the chosen elements representative of the population being considered (Kalton, 1983). Moreover, the survey carried out is an attempt to uncover relationships that occur between variables and to gain insight into some aspects of the present, thereby categorizing the survey as a descriptive study. In summary, propositions were made for a broad-spectrum achievement of an increased share in the stated renewable energy objectives

5.2 Energy survey research design

In view of the second research gap and with specific focus on energy targets set by the European Commission, of which the UK is represented at the moment, there are targets put in place for appreciable achievement of the set goals. Moreover, in order to realize full benefits from the impact of the set targets, an extensive analysis of practices and their effects on all stake holders involved is required. However, special focus has been placed on the demand side (individual consumers) of the energy supply chain. As a result of this and by data gathering, a mixed method of both quantitative and qualitative survey has been utilized. As the developed survey is the mixed model type, consisting of both quantitative and qualitative types of questions, the data obtained from the quantitative questions assist in making the bigger picture clearer, while the responses from the qualitative questions represent human perceptions of the survey.

The survey questions on energy types, generation and usage were developed with the use of Qualtrics online survey tool, which has the advantage of being cost and time effective. Further, target respondents were chosen from UK residents in selected areas around Bedfordshire, Buckinghamshire and Greater London counties. However, there were negligible share of respondents from other counties and all have been grouped together under “Others” category.

5.3 Energy survey with consideration given to the UK energy mix

In order to better understand the acceptability level of renewable energy in the UK and propose strategies that will improve its embracement, energy survey questionnaires were developed and distributed to target respondents in some counties of the UK. Peoples' perceived understanding on the proposed energy questions were put into consideration and inherent professional bias on the subject matter was eliminated. This was necessary in order not to trigger a lack of interest in answers that will be obtained from the target respondents, which is likely to occur if the survey questions are too technical. In this instance, respondents may only provide answers which are not a true reflection of their perceptions or feelings on the focal questions.

Notwithstanding, the survey consists of 18 multiple choice questions and two open ended questions. It is worth noting that, the multiple choice questions are segmented into four different sub headings and analysed accordingly. Section A comprising the demographics of the target respondents, with a look at respondents' age, gender, level of education as well as occupation/profession. Moreover, locations of the respondents were identified and noted from the IP addresses obtained in the survey report and respondents' percentage distributions based on their various localities is represented by Figure 5-1. Additionally, various medium of awareness of RETs, which was used in the measurement of respondents' awareness levels on renewable energy was also analysed in this section. Section B consinders incentives that are put in place for renewable energy generation and usage, in addition to satisfaction derived from renewable energy usage. In Section C, planned areas of renewable energy exploration and reasons for renewable energy exploration are considered, while Section D deals with energy generation and usage levels, costs, recommendations and impact of improved Government's policies on RETs

Additionally and of utmost importance in the survey were the applicable percentages on various options that were selected as most of the questions developed were closed-ended questions, this was necessary as it clearly indicated percentages of selection for each question being considered (Moula *et al.*, 2013). Study respondents were categorized into four different selected age groups (16-25; 25-40; 40-65 and above 65) years. From the age categorization, a total number of 85 individuals responded to the survey, five from (16-25), 49 from age group (25-40), 30 from (40-65) and one from above 65 years of age. These age groups have been specially chosen in order to identify the effect of different ages on improving the level of renewable energy embracement in UK energy mix. A total of 23.54% of the respondents are employed in stated occupation, while 35.29% have their occupations from other sectors that are not categorized in the questionnaires.

The survey was conducted between January and July 2019, with the respondents covering some areas in the counties of Bedfordshire, Buckinghamshire, Greater London and other counties that had negligible number of respondents. In essence, these counties that suggested the potential of a negligible number of respondents were all grouped together as “Others”. 47% respondents were from Bedfordshire, while, 12% were from Buckinghamshire, 20% from Greater London and 21% from other counties in the UK.

After the survey responses were received, quantitative analysis of collated data was carried out as various survey choices obtained from respondents were represented as percentages of a whole. Moreover, in-depth analysis of the responses obtained was utilized to determine embedded perceptions, subject matter and, in the identification of distinguishing topics within a given set of texts (Berg, 2009). It also provided direction as regards implementations that need to be carried out in order to improve the level of renewable energy in the UK energy mix. Furthermore, an appreciable level of qualitative conclusions as a result of the quantitative analysis were inferred.

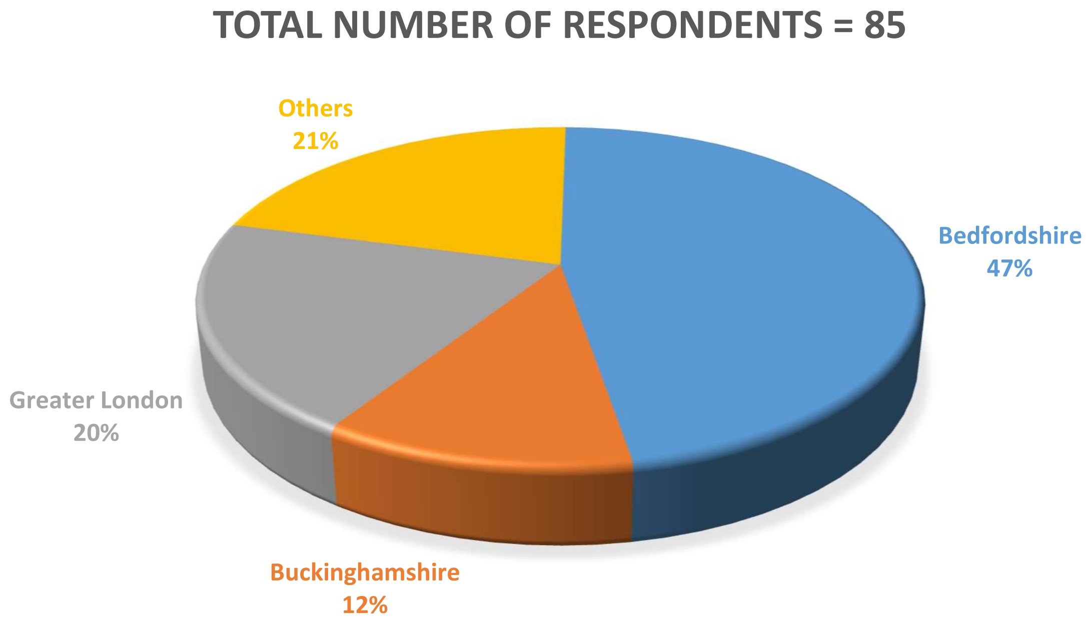


Figure 5-1Share of survey respondents from target counties in the UK

5.4 Energy survey results, analysis and discussion

With the net zero emissions target set in the UK for the year 2050, all stakeholders on the energy supply chain networks, right from government, who set the policies, to energy generators/producers, all the way through to consumers must be fully involved in processes and activities towards the achievement of this goal. This implies that, after the year 2050, there will be a legally binding target on the UK to absorb the same amount of emissions made into the atmosphere. However, this act is to amend the Climate Change Act, 2008 and it's aimed at public health, air quality and biodiversity improvement. Moreover, it implies that the UK is set to become the first G7 country to legislate for net zero emissions. The net zero target would mean wholesale changes to home heating, transport, and even people's diets (Sky News, 2019). In view of this development, energy survey was conducted in some counties of the UK and the responses obtained are analysed and discussed in the next sections.

5.4.1 Section A: Background information of respondents and awareness level on renewable energy technologies

Survey participants were drawn from different age groups in order to have a diversified opinion on the effect of age on the survey results as shown in Figure 5-2, Individuals in the middle age groups of 25-40 years and 40-65 years accounted for a total of 92.94% of the survey respondents. This value, however, was distributed, with the early middle age group (25-40 years) accounting for 57.65%, while the later middle age group (40-65 years) accounted for 35.29%. Low percentage shares of 5.88% and 1.18% were predicted amongst respondents in the age groups; 16-25 years and above 65 years respectively, which may have been as a result of utilizing the snowballing sampling methods in the course of the survey.

As expected, the age groups that suggested the potential of the highest shares of renewable energy use are those that can be categorized as being in the early and later middle age groups (25-40 years and 40-65 years), who most often are living on their own, and as such, are responsible for most of their energy decisions, such as preference for energy types as well as bills payment. The values predicted however, indicate their support for renewable energy use and as such, they are responsible for their decisions as regards basic necessities and utilities of life. Further, from the responses obtained from the survey, and drawing a comparison between age and renewable energy embracement, and in contrast to the general findings obtained from the study of Moula et al. (2014), the two categories of middle age respondents, both the early (25-40 years) and the later (40-65 years) are more supportive of renewable energy technology than the younger age group (16-25 years) and the older age group (above 65 years)

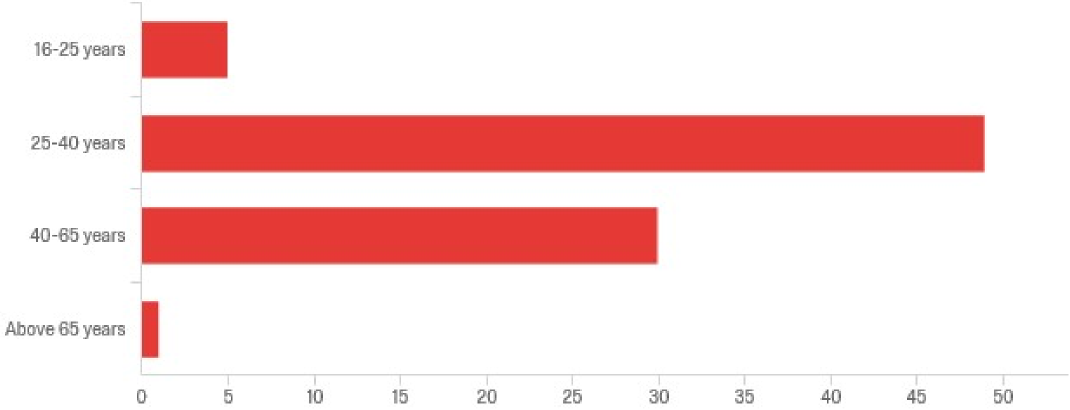


Figure 5-2 Age of survey respondents from target counties in the UK

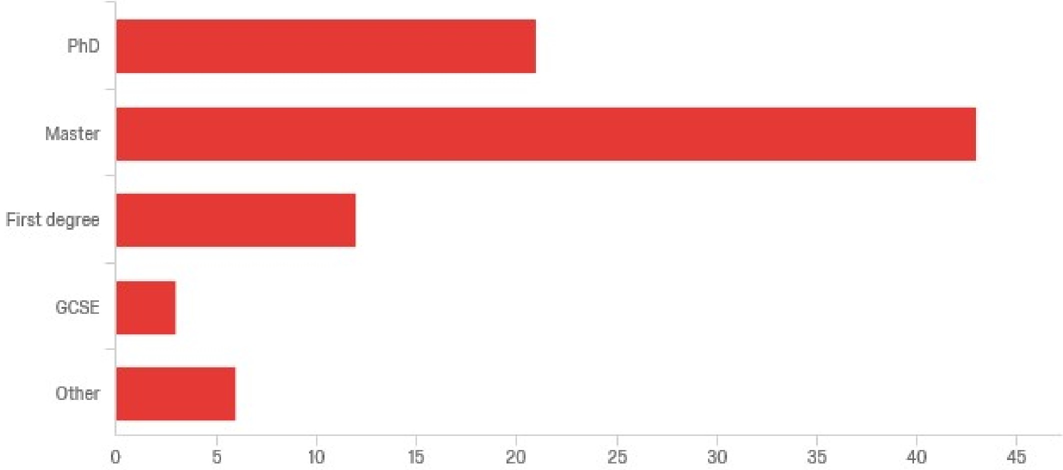


Figure 5-3 Respondents' degree/level of qualification

Moreover, with 75.3% of respondents xxx having advanced degree and 7.06% categorized in the "others" group, who may have very minimal level of education, it indicates to a large extent that, irrespective of the level of education, knowledge on energy, as a global concern, cuts across all cadres of educational qualifications, as most questions had full representations in terms of responses obtained.

Additionally, from analysis carried out from the question that deals with preferred types of energy in use by respondents, out of the total of 10.59% obtained for renewable energy usage, 5.88%, (which was more than half of the total applicable percentage) was attributed to respondents in the age group, 25-40 years, while, 3.53% was the share for respondents in the age group; 40-65 years. However, the younger age group, 16-25 years had a share of 1.18%, while there was none predicted against the older age group of above 65 years, indicating that, these age groups with lower values may not make decisions as regards their energy usage at the time of conducting the survey.

Moreover, a study into the profession of respondents indicated that, 41.18% of the total respondents were students, closely followed by 35.29%, whose occupation and profession belonged to the group of other professions/occupations not listed. However, the respondents who fall in this group are assumed to have varying professions and occupations, indicating a high diversity in the responses obtained. In essence, this is a good indication for the survey in order to arrive at very good energy propositions and also towards making robust energy decisions. Furthermore, as shown in Figure 5-4, respondents who were lecturers made up a total of 10.59%, while Managers, Operators and people in government accounted for 7.06%, 4.71% and 1.18% respectively.

Overall, the list of professions and occupations may further be grouped under employed and students, with the totality of Lecturers, Operators, Managers, Government and Others categorized as those in the employed group, while students make up the other group. In this case, 58.82% make up the employed group, while, 41.18% account for those that are students as shown in the results obtained.

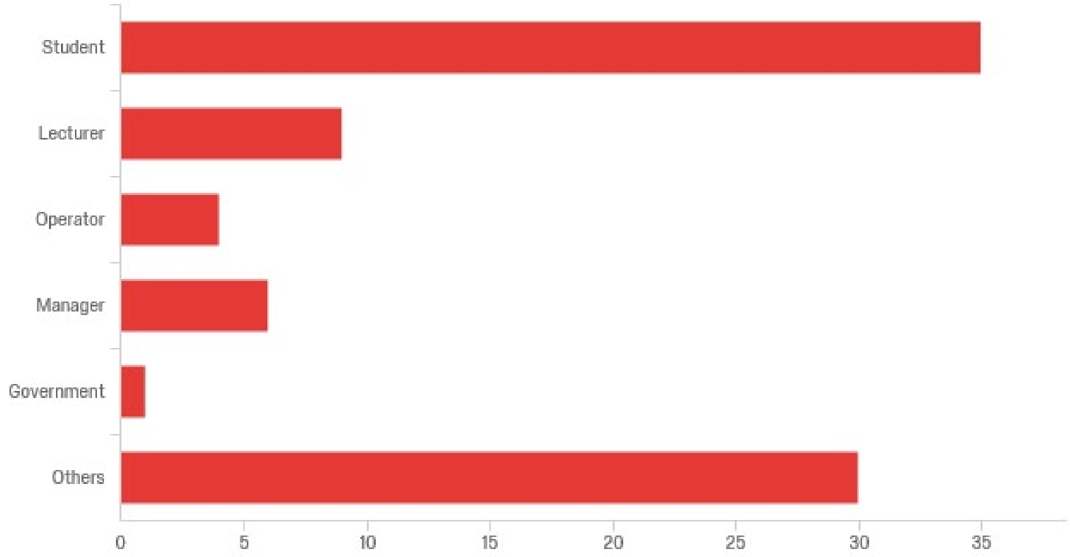


Figure 5-4 Respondents profession/industry category

A further look at the question that enquired on the attributes that respondents like most about renewable energy, a total of 48.23% respondents stated that the environmental protection attribute of renewable energy usage is an attraction for them. Further, the share of survey respondents who aligned with cost reduction and cleanliness were 9.41% and 8.24% respectively, while the combination of respondents who were indifferent and those that did not provide any response to the question made up a total of 34.12%, a large percentage that could be attributed to the percentage of respondents that said their source of energy generation is strictly conventional/fossil fuels (40.00%), which is an indication of low awareness on the benefits that renewable energy have to offer. In the report by Moula *et al.* (2013) in their survey on Finnish residents, they reported that majority of respondents who have the perception that, their actions will in no way have any effect on climate change are found more amongst the younger generation. However, a record, slightly different to that was obtained in the case of sampled UK residents. Upon analyzing the 13 individuals (15.29%) who did not give a response to the survey question which looked into the positive attributes of renewable energy that could increase its embracement and thus, its share in the current UK energy mix, It is Interesting to note that, 53.84% (7 out of 13 respondents) were in the age group of 40-65 years, implying that, the horizon is left for government, researchers and others, who have indicated their views on positive benefits of renewable energy embracement to lay emphasis on it and share its knowledge on a global scale (via social media) for the purpose of awareness creation: These results, however, lead to the first proposed strategy of increased awareness of renewable energy and its benefits in order to improve its share in the UK energy mix. Further, it can be observed that, the need for deliberate efforts towards raising awareness in level of RETs, coupled with its inherent benefits, both on the generation and usage sides is inevitable.

Moreover, a look at the question which pointed out at how likely a respondent was willing to introduce renewable energy to a colleague or friend shows 48% of the respondents happen to be promoters of renewable energy technology, with 30% being passive about it and 22% being detractors, with the combined percentage of respondents who are detractors as well as those who are passive about RE introduction to friends accounting for over half of the respondents. In order to record a substantial achievement on the long- term target set by the UK government at achieving a net zero position on GHG emissions by the year, 2050 . In essence, robust efforts must be put in place on awareness creation in order to reach the stated goal.

Furthermore, from the data obtained from level of effectiveness of print media at improving the embracement of RETs in the UK, it is evident that, more than three quarters of the respondents (80.95%, which is a combination of those who chose ‘very effective’ and ‘somewhat effective’ options) feel posters, fliers, leaflets, billboards, radio and television adverts will constitute positive avenues at improving renewable energy embracement in the UK. Likewise, with the high share (88.19%) obtained from responses on increasing awareness level through internet and social media, there is no doubt that, individual energy consumers or generators will not welcome a raise in awareness level through this media at communicating the inherent benefits of economic, environmental and social aspects that are associated with renewable energy generation and usage.

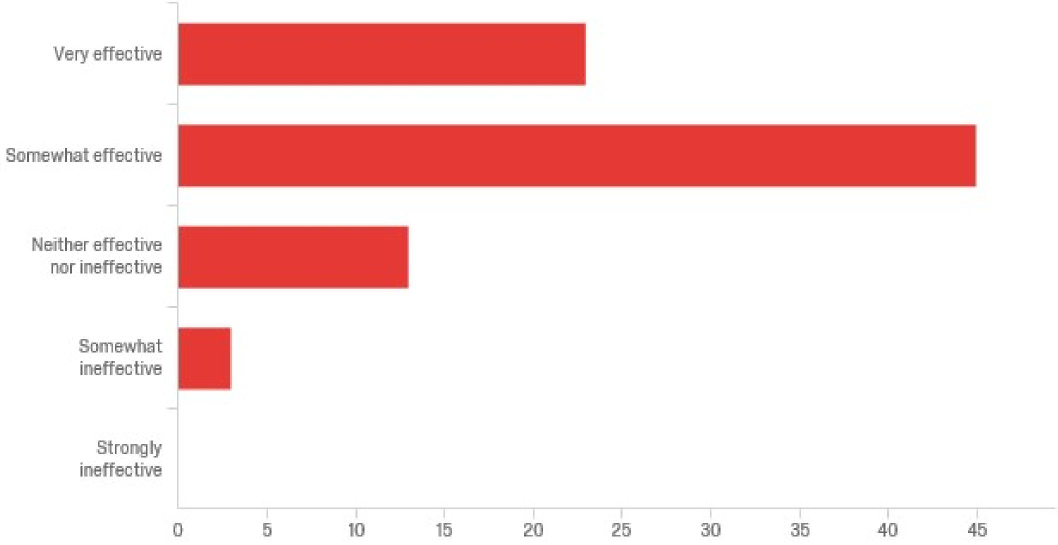


Figure 5-5 Medium of awareness of renewable energy

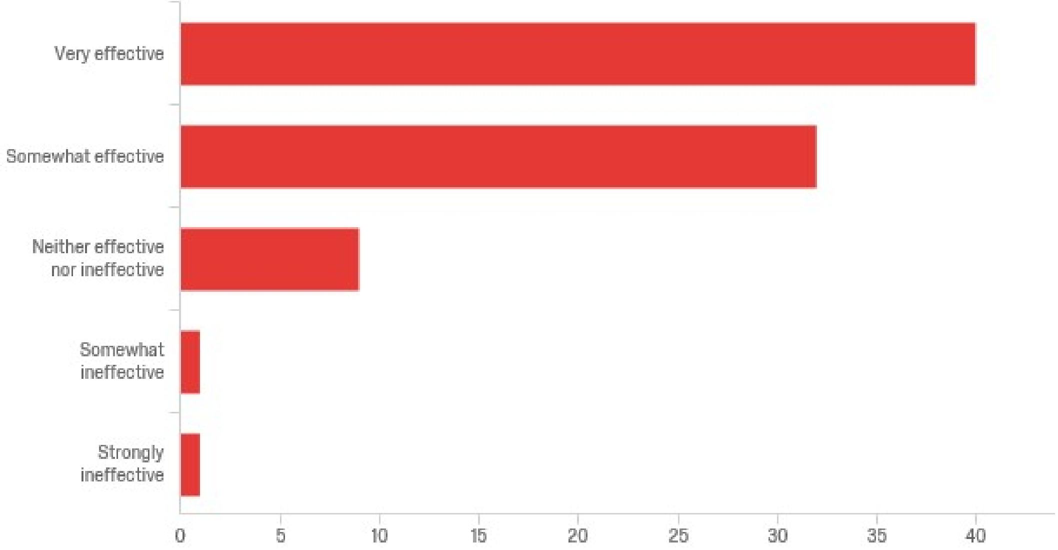


Figure 5-6 Level of effectiveness of internet and social media

5.4.2 Section B: Impact of incentives on renewable energy technologies

Additionally, from the percentage predicted on greener environment (54.12%) as a reason for exploration of RETs, indicating a share that is more than half of the surveyed respondents, it clearly shows that, individual consumers care about the environment in which they live in and are aware of the environmental benefits they stand to gain when renewable energy is embraced, however, it is possible that the 25.88% (Figure 5-8), who initially gave a not applicable response to planned areas of renewable energy exploration, may actually not have the resources to invest in such venture, which corroborates the proposition on the need for the introduction of government's incentives for renewable energy generation and usage to individual consumers. Moreover, if the costs on renewables is cheaper than that obtained from conventional sources of energy, then, an increased level of embracement of RETs may be predicted.

Moreover, as shown in Figure 5-7, 87.63% of respondents have indicated that, with government's incentive in place, there would be an improvement in embracement of RETs in comparison to 2.38% who gave a 'definitely not' response. Considering these results, asides from the Government or the public sector providing more transparent information on renewables business model to individual consumers, it is obvious that everyone would love the cheapest energy option offered to them. As such, the government must sustainably work at availing cost on energy models which are cheaper or at the very least equal to the cost of consumers' energy expenditure on conventional sources of energy generation and usage. Moreover, if the government decides on the former option of a cheaper cost on renewable energy sources, then sustainable, available and working incentives must be in place in order for such proposition to be achieved. On the other hand, if the latter option of equality in costs of renewable and conventional sources of energy is embraced, then, awareness on advantages on the generation and usage of energy from renewable sources should be clearly made available to consumers, from enablement of green environment, having good and quality air to breathe, prevention of natural disasters such as floods, droughts, storms, reduction in depletion of the ozone layer and avoidance in shift of the natural ecosystem.

Further in the survey, the overall percentage of respondents who have indicated their satisfaction with renewable energy usage (58.07%), is higher, compared to a total of 10.84% who gave the options of 'moderately dissatisfied,' (7.23%) and ‘extremely dissatisfied’, (3.61%). Their predicted opinions still lead us back to the importance of conscious efforts at raising awareness level of consumers on the ESC networks. However, with the percentage obtained on consumers who are satisfied with RE usage, it shows an appreciable level of support for renewable energy generation and usage in surveyed areas of the UK. Nevertheless, more work still needs to be done at appropriate sensitization of the remaining 32.53% of respondents who are indifferent about renewable energy usage.

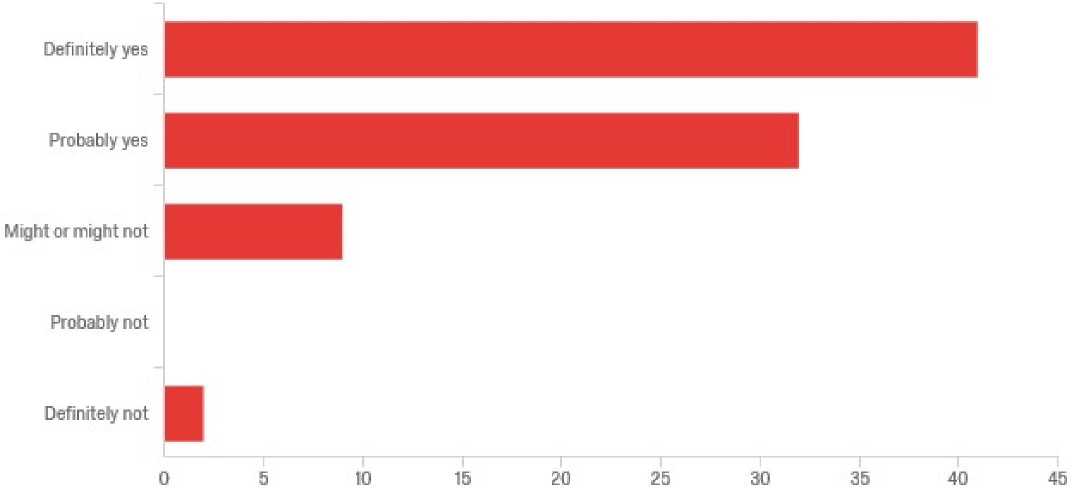


Figure 5-7 Incentives on renewable energy generation

5.4.3 Section C: Introduction of varying energy mix

The question that deals with preferred area of renewable energy for exploration puts to test participants’ understanding on types of renewable energy sources and their awareness on applicable technologies. As indicated in Figure 5-8, participants are presented with six different choices, namely, biomass, geothermal power, marine power, solar power, wind power and the last option of non-applicability of any of the choices. As noted, about 74.12% of respondents have knowledge on one or two types of renewable energy technologies, with 25.88% coming under the “not applicable” option. This question can be considered as an informative one which tested the knowledge of at least 85 people on existing RETs, but it was not expressed in such a way as to determine the current awareness of each specific technology amongst respondents.

Moreover, from Figure 5-8, 49.41% of the total respondents have indicated that, they explore or would like to explore renewable energy from solar source. This is a bit contradictory to reports obtained from research and execution projects on the resistances that people show when solar panels are considered for implementation on their roof tops, as they are said to obstruct their views and also cannot accommodate their noise levels These given reasons, however, point to the fact that, the perceived hesitation may be as a result of its uncommon occurrence in their locality.

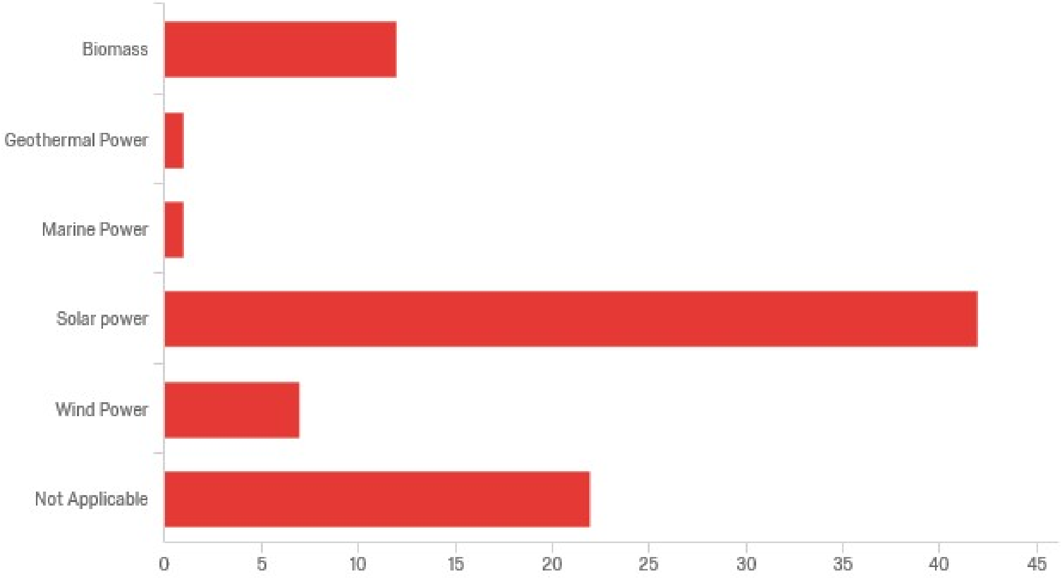


Figure 5-8 Renewable energy area for exploration

However, the low percentage obtained for wind energy (7%) confirms peoples' opinions on resistance shown for small-scale wind turbines in their courtyards, but this is in contrast with the opinion obtained from the studies of Khambalkar *et al.* (2010), opinions of the public suggested their preference for renewable energy obtained from wind source, but also had a common opinion that, for a reduction in global warming to be achieved, renewable energy from solar sources should be embraced.

5.4.4 Section D: Improvement in Government policy

A further investigation in the survey question on the type of energy in use at the moment by the respondents gives the breakdown as shown in Figure 5-9, with the share of respondents using only renewable source of energy generation as 10.59%. However, respondents in the age group 25-40 years, who also use renewable sources of energy generation was 5.30%, which amounts exactly to 50% of the total share of respondents using renewable source of energy. With a share of 3.97% corresponding to respondents in age groups 40-65 years, this implies that target respondents in the early middle age group (25-40 years) and later middle age (40-65 years) are more supportive of renewable energy technology than the younger age group (16-25 years), a percentage of 1.32% and the older age group (above 65 years), which had no representation at all.

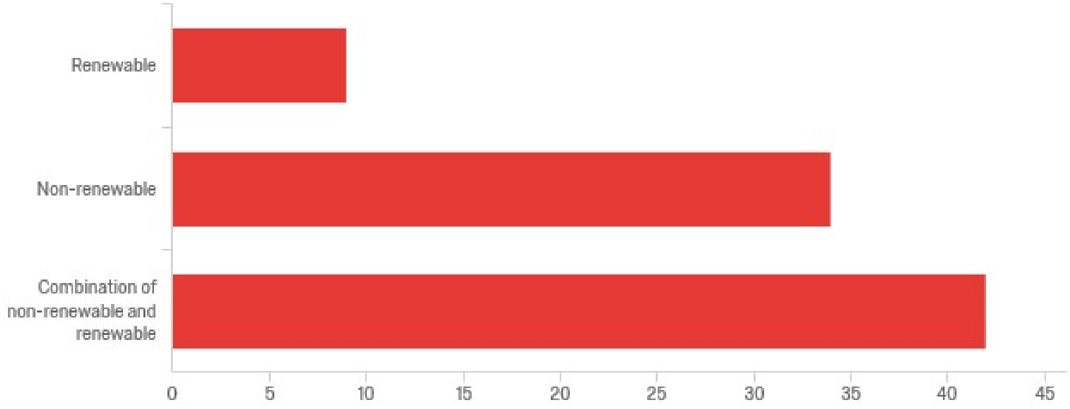


Figure 5-9 Type of energy in use by respondents

Moreover, the implication of responses obtained from the survey carried out on renewable energy generation and usage can be summarized as shown below:

- 32.14% of respondents or respondents' company that generate renewable energy (RE), while 50.59% use one form of renewable energy or the other.
- Further analysis shows that, out of 67.86% of respondents who do not produce sources of renewable energy, only 36.47% do not use it, indicating that deliberate and sustainable efforts on policies and incentives for renewable energy generation and usage must be put in place by the government to ensure an increase in use in the 2018 level reported in the UK at 33% and at a percentage level of 37.4% thus far in 2019 (UK Department for Business Energy & Industrial Strategy, 2019).

- However, 14.29% of respondents were indifferent on RE generation, while 12.94% respondents were indifferent on its usage.

Moreover, from respondents' embracement or planned embracement of solar power, it shows individuals 'support for renewable energy sources that have the ability of meeting the demands of consumers, with simultaneous provision on security of energy supply are considered as a good option. Moreover, it suggests that, improvement in policies, such as solar tax credit should be implemented sustainably in order to achieve an improvement in the level of renewable energy embracement. Additionally, considering a percentage of 87.05%, of respondents, (Figure 5-10) who think there could be a shift from the conventional sources of energy generation and usage, a share that is over three quarters of the total respondents, this figure clearly shows that a promising result will be obtained for improved renewables embracement in the UK if Government policies on RETs are robust, sustainable and improved upon.

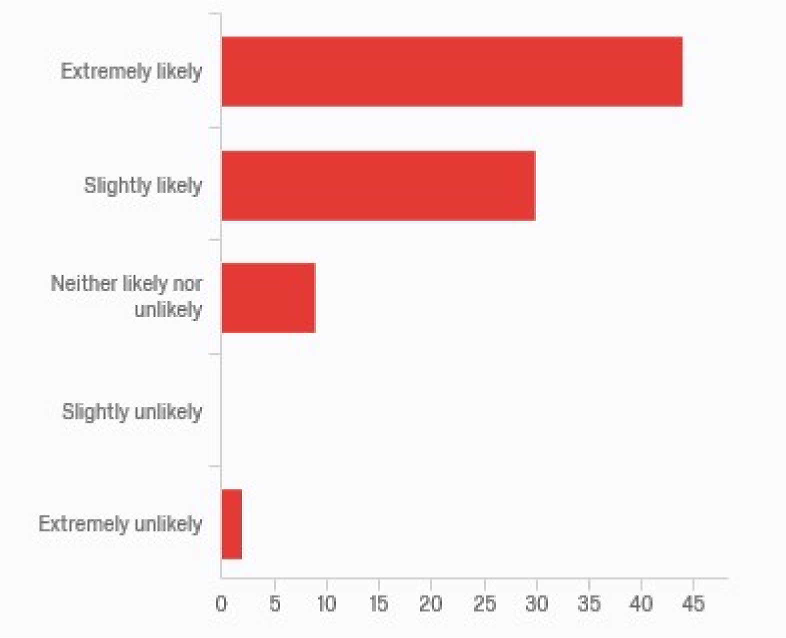


Figure 5-10 Shift from conventional sources of energy generation and usage

5.4.5 Propositions for improved renewables embracement in the UK energy mix

From the quantitative analysis performed on collated data that were obtained from disseminated questionnaires to survey respondents, it has availed the opportunity for strategies on improved RE embracement in the considered environment to be proposed. Moreover, if the strategies listed below are adequately implemented, expected results would be achieved.

- Raise in consumer awareness on inherent benefits of economic, environmental, social and health areas that are associated with renewable energy generation and usage. This could be achieved through the use of the internet, social media, posters, fliers, bill boards, television and radio adverts.
- There should be an introduction of a fair, stable and working financial incentive policy for an appreciable number of years on the demand side (individual consumers) of the supply chain, such as Individual Renewable Energy Usage Tax Credit (IREUTC). This proposition is in line with the Production Tax Credit (PTC) in place for renewable energy facilities in the US and will go a long way at achieving the targets set around the 2020, 2030 and 2050 energy policy frameworks.
- Additionally, government could introduce varying energy mix on new buildings going forward. In view of the proposition stated, a proportion of household heat and power generation sources from renewable energies could be introduced instead of the conventional gas, heating and electricity supply from non-renewables sources of fuel.
- Improvement and sustainability in policies such as solar tax credit as well as its extension to individual consumers in order to achieve a higher level of renewable energy embracement.

6 GENERAL DISCUSSION

As reduction in global greenhouse gas emissions is a very important necessity for the mitigation of global climate change, which is an increasingly important priority, then, highly reliable and secured energy networks with increased efficiency obtained at the most reduced cost possible is of utmost importance. As such, the deployment of an all-inclusive decarbonisation measures over all sectors of the energy system must be emplaced.

In order to achieve decarbonisation of the power sector, by the year 2050, renewables, low carbon technologies as well as carbon capture and storage (CCS) need to be generated, produced and deployed at a rate that will drastically shift the overdependence currently experienced on energy generated from fossil fuel sources. While the composition of both natural gas and oil are 23% and 4% respectively, a look at coal records its share as one-third in the global energy usage and at 38% of global electricity generation, indicating a very high usage of energy obtained from their sources (IEA, 2018a). Unfortunately, these fossil fuels, aside from their non-renewable nature, also account for over 70% of global CO_2 emissions. However, a look at coal indicates a legend of two worlds, whilst there are policies in place in an increasing number of countries as regards concerted efforts towards visible and sustainable reduction in its generation and usage; it remains a vital source of electricity in others due to its abundance and affordable nature (Sadamori, 2018). In view of this, appropriate design and planning of coal-fired ESC networks with optimization-based approaches is inevitable. Moreover, efficient planning of energy production and maintenance of large-scale combined heat and power plants using simultaneous approach has not only proven to be time and cost effective, but also, their implementation leads to improvement in resource and energy efficiency (Chapter 3) of the power plant.

In order to achieve the objectives of this research project, optimization models were formulated and developed using mixed integer linear programming methods, with same implemented and solved using the GAMS software. Additionally, the applicability and key limitations of the models and methodologies are summarized in Table 6-1. This is necessary in order to ensure that the proposed models are reliable and performing as expected in accordance with their design and planning objectives as well as their business uses. Furthermore, assumptions were made as well as their possible impacts on the proposed models; these models were validated against available data and obtainable results from open literature.

Table 6-1: Applicability and limitations of the developed optimization models

Models	Key limitations	Applicability
A MILP/MIP model for simultaneous planning of energy production and maintenance of coal-fired CHP plants	The Management of the power plant could not provide some technical and cost related data due to confidentiality issues	The developed model has been applied to the largest coal-fired CHP plant in Kazakhstan, which is also known as the KUS.
A generalized MILP/MIP STN deterministic model for co-firing biomass with coal	• No consideration of the solid fuel characteristics that could affect range of biomass quantity that could be co-fired with coal.	The developed model is applicable to a biomass (woodchips) and coal co-fired power plant and has been validated with data obtained from literature.
	• Seasonality of biomass supply and technical challenges of its implementation in co-fired systems, such as slagging, fouling and corrosion were not considered (IEA-ETSAP and IRENA, 2013).	

Furthermore, as regards the method of approach in the conduct of the energy survey, the non-probability sampling method, which is characterized by individuality (Kalton, 1983) was used. This excludes build-up of a theoretical framework for its entirety, and as such, sampling error is not represented, which resulted in the probability of inability to generalize the outcomes/results.

Moreover, the size of respondents was small (85 in total), but of varying backgrounds, indicating that a sample of this order cannot represent appropriately the standpoint and perception of all the British society in accordance with strategies to improve the level of renewable energy embracement. However, it can be a reflection of a good commencement in conducting extended surveys in the future. Additionally, as with online and mobile surveys which are cost effective, may not have reached respondents that can only give their responses through alternate modes.

Nevertheless, from reported predominance of fossil fuels in the global energy mix at the moment and its continual increment into the future IEA (2019), considerable efforts aimed at integrating renewables into energy supply chain networks will not be left unattended. The use of low carbon technologies, such as, nuclear, wind, solar and hydroelectricity for electricity and heat generation is considered as energy sources for GHG emissions reduction. Yet, as nuclear energy (whose operation process harvests the strong energy in the nucleus of an atom) itself is a renewable energy source, the material used in nuclear power plant is not renewable. As such, optimization approach in verifying the range of biomass mixed with coal to reduce the effect of emissions into the atmosphere, thereby mitigating climate change and contributing to energy supply network is important.

Moreover, as shown in section 3.3, the proposed simultaneous energy production and maintenance planning optimization approach suggested the potential of a remarkable decrement of 21.2% in comparison to that obtained at the industry (KUS), with the cost components that made up this reduction consisting of the fuel costs, fixed operating costs as well as startup and shutdown costs. Moreover, it shows clearly that, simultaneous optimization approach achieve the under listed:

- Avoid unnecessary startups and shutdowns of boiler and turbine units;
- Significant reduction in fuel consumption, while energy demand is fully satisfied and
- Increment in energy and resource efficiency of power plants.

In as much as overall cost reduction of 21% was predicted on the coal-fired CHP plant, which is a fossil fuel-based ESC. it still does not take away the fact that its use constitutes a high percentage of global GHG emissions and as such, considerable efforts at reducing the level of CO_2 emissions, the most abundant

GHG in earth’s atmosphere after water vapour has been achieved by the introduction of renewables, specifically, biomass into a coal-fired power plant.

In section 4.5, results of the proposed optimization performed on the dual fuel fired (biomass plus coal) power plant, using the STN approach and implemented on the GAMS software predicted a reduction in cost of emissions of up to 4.32%, which was achieved on integrating 5-8% of biomass in accordance to a maximum feasible 10% co-firing ratio reported in literature. However, at a biomass fraction of 7.9%, there was an increment of 4.57% in the overall cost of the ESC, with the fixed asset cost taking up the largest share of the increment. This observation, however, is because of additional and more complex processes of integrating biomass into coal-fired supply chain networks. Moreover, with most previous studies on minimizing the total cost of ESC networks with biomass integration following the multi-period super-structural model, the model presented follows the state-task network (STN) approach. The unique characteristics of the STN approach lie in its composition of two types of nodes, the state nodes and the task nodes, which is also known as the process operations nodes. With such configuration, process operations are distinguished from the resources used in performing them. Additionally, the proposed general modelling technique considers a unified management of both material and energy supply chain networks embedded within a unique optimization framework. Although, the trend on emissions reduction obtained when biomass is co-fired with coal is promising, however, the rate at which low carbon technologies are implemented in ESC networks may not be sufficient to meet the desired emission reduction targets. As such, strategies for improvement in energy generation and usage (by individuals) using renewables was inferred in section 5.4, with a survey conducted on some counties in the UK and summarized as follow:

- Raise in consumer awareness on RETs;
- Government and public sector should make available, sustainable financial incentives to individual generators and consumers that will translate to improve embracement of RETs;
- Subsequent introduction of an agreed percentage of renewables in energy mix of new buildings and

- Improvement in policies governing individuals' renewable energy generation and usage.

With consideration given to identified gaps in knowledge which were not covered in the course of conducting this research, thereby leading to the limitations of this work, recommendations for the conduct of further studies are hereby proposed.

In the case of production and maintenance planning of a large-scale combined heat and power plant, extensive data analysis could be carried out with the purpose of deriving suitable performance degradation and recovery models for the boilers and turbines that would result in a maintenance strategy that considers explicitly the conditions of this major equipment. With consideration given to the case study of integrating biomass into energy supply chain networks, propositions for further research are stated below.

- Consideration of alternative biomass types for the purpose of co-firing with coal;
- Consideration of other base fuels alternative to coal, such as oil or gas;

- Incorporating a stochastic approach to quantify effect of uncertainty and
- Accounting for the biogenic emissions.

In addition, with different types of biomass having significantly different physical and chemical compositions that may have a substantial effect on the outcome of processes performed on their energy supply chain networks. It is recommended that further analysis be performed to determine the validity of the current prediction if other types of biomass are used. Moreover, further studies could look into generation expansion planning (GEP) with carbon capture and storage (CCS) technologies

Finally, as regards strategies for improvement in renewable energy technology embracement in the UK, areas of future work to be explored could include the conduct of extensive and integrative research with the use of advanced and original mix of both quantitative and qualitative research methods with great emphasis on perceptions of RETs by the public. Additionally, future surveys should include more counties in the UK.

7 CONCLUSIONS

From the work conducted within the scope of this PhD project, appreciable contributions have been made to the scientific body of knowledge in areas of overall cost reduction in CHP plants, using simultaneous operations and maintenance planning. Additionally, suggested emissions level was reduced by integrating biomass into coal-fired ESC networks. Further, propositions for improved renewables embracement in the UK energy mix are suggested.

7.1 Efficient planning of energy production and maintenanceof large-scale combined heat and power plant

In the case study of the largest coal fired combined heat and power (CHP) plant in Karaganda (the KUS), a general optimization model for the integrated planning of energy production and maintenance has been developed and applied on the power plant, with necessary input data extracted from those data that were made available by the management of the power plant. The case study demonstrated clearly the significant benefits of the proposed optimization-based approach and more specifically, the solutions obtained by the proposed approach achieve reductions in annual total cost more than 21% and totally avoided turbines operation outside their desired operating regions, in comparison to the industrial solution. Additionally, the solutions report substantial reductions in startup/shutdown, fuel and fixed operating costs, and improved energy efficiency of the cogeneration plant. Overall, the comparative case study has demonstrated clearly that the proposed approach is a much more effective means for generating optimal energy production and maintenance plans than the current industrial policy. Moreover, the proposed optimization model could readily be applied to other cogeneration plants that follow a similar plant structure.

7.2 Integrating biomass into energy supply chain networks

The integration of biomass and its co-firing in a coal-fired CHP plant is one of the most cost-effective methods of generating electricity from biomass and achieving significant reductions in GHG emissions. Moreover, this will translate to an increased level of energy security, thereby guaranteeing a reduction on the dependence on imported fuel, leading to an improvement in economic development. This case study focused on emissions reduction and its overall effect on the total cost of the ESC network with biomass integration in the mixed solid fuel with the use of STN approach. With the results of the optimisation revealing that at biomass fraction of 7.9% in the mixed solid fuel, while the emissions level of the ESC network was reduced by 4.32%, the overall cost of the network was increased by 4.57%. Although, as predicted by the proposed model, biomass (wood chips) fractions in the mixed solid fuel in the range of between 5% and 8% could be co-fired with coal to achieve an appreciable level of emissions reduction and at affordable cost. However, biomass composition of 7.9% resulted in more balanced values on other cost components of the considered ESC network. Additionally, the cost increment in the fixed assets and operational costs of biomass and coal co-fired CHP plants could be offset by the cost reductions obtained from reduced CO_2 emissions with effective carbon pricing legislations in place. Furthermore, the cost considered in the ESC networks is the overall cost of the supply chain, while the monetary values were not discounted due to interest rate.

This study shows that, in addition to the environmental benefits realised from biomass integration into the existing ESC network aimed at mitigating climate change due to emissions from thermochemical conversion of fossil fuels, economic benefits are achievable if relevant carbon pricing legislations are implemented. As such, decision makers in the power industry can justify their reasons for co-firing biomass with coal.

7.3 Strategies for improved embracement of renewable energy in the UK energy mix

Asides the results that were obtained on the quantitative analysis of respondents' data in the energy survey conducted, an in-depth study of the completed questionnaires also revealed variations in individuals' circumstances. In view of this, it was obvious that individuals that are in the early and late middle age groups, (25-40 years and 40-65 years), had increased awareness of renewable energy technology, a higher level of responsibility about problems in the environment as well as renewable energy technologies in the surveyed counties in the UK. Most especially, a large percentage of these individuals are also in the employed group. For most young people, especially those in age group (16-25 years), who may not be responsible for payment of their energy bills, their level of awareness on importance of RETs, could still be increased, if appropriate steps are taken at ensuring same. Moreover, results obtained from the conducted survey reveal that, as regards the sample frame, the extent of awareness and understanding of various energy technologies alongside their effects show mixed set of reactions, which is because of the different questions asked in addition to dissimilar backgrounds of the respondents.

However, the main objective of the survey conducted was to learn about effect of UK individual consumers (with a special focus on specified counties) and generators on the ESC network and further propose strategies to improve renewables embracement on such networks. Based on the quantitative analysis conducted, qualitative conclusions were drawn. About 74.12% of respondents would like to take practicable measures on renewable energy exploration, with 87.63% acknowledging the fact that, incentives from the government will go a long way at achieving their objectives However, this study also revealed lack of indifference on sources of renewable energy areas for exploration by the remaining 25.88% of respondents. The survey results also show that all respondents have one reason or the other for wanting to explore renewable energy, with the highest share (54.12%) stating their reasons as the greener environment that is obtainable with renewable energy embracement. Moreover, 34.12% of respondents stated that, it is cost reduction obtained from renewable energy, which may be achieved if effective carbon pricing legislation is in place as in the case of biomass and coal co-fired CHP plant, in addition to sustainable incentives from the part of the government. However, a small share of 11.76% of respondents mentioned revenue generation as their reasons for exploring or planning to explore energy from renewable sources. The responses obtained, to some extent show individual consumers' awareness of some beneficial areas of RETs, irrespective of some being indifferent about the technology itself. However, this level of awareness calls for improvement in order to achieve of emissions reduction goals.

Finally, as the stage is set for renewables’ sustainability in the global energy mix, of which the UK is a part of, the role of the government in advancing renewable or green energy is greatly required. Moreover, encouragement from the government is essential for the development of domestic use of renewable energy, as its conceptualization in the near future is highly important. Additionally, respondents have indicated that the role played by the internet and social media and advertisements through various media, such as fliers, radio and television is very prominent at increasing the awareness on RETs.

In summary, more than three quarters of the respondents think that a shift is imminent from conventional sources of energy generation; yet, the public’s viewpoints on issues surrounding RETs are different from those of energy specialists. As such, asides from clarification of individuals’ awareness on the importance of using renewable energy technology and all variables that will achieve its improved embracement, the general public should be given the opportunity to gain more understanding on benefits inherent with using RETs.

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APPENDICES

Appendix A **GAMs equation codes for the case study of combined heat and power plants at Karaganda utility system (KUS)**

A.1 Equation codes for optimized case (OPT-3)

```
$TITLE KUS CHP PLANT (KUS_01, SEQ=1)

OPTIONS

iterlim = 100000, limrow = 1000, limcol = 0, reslim = 28000, mip =
cplex, optca = 0.00, optcr = 0.00;

*solprint = off;

$offlisting $offsymxref offsymlist

$include Data

PARAMETERS

psi(i)        minimum offline time after the shutdown of processing unit
              i (minimum shutdown time)

psip(i)       total number of time periods at the end of the past
              prediction horizon that unit i has been continuously off-
              line since its last shutdown

omega(i)      minimum online time after the startup of processing unit i
              (minimum run time)

omegap(i)     total number of time periods at the end of the past
              prediction horizon that unit i has been continuously on-
              line since its last startup

tes(i)        earliest starting time of maintenance task of processing
              unit i that belongs to IFM(i)

tls(i)        latest starting time of maintenance task of processing unit
              i that belongs to IFM(i)

 ni(i)              duration of maintenance task in processing unit i

 nip(i)        total time of time periods that unit i has been under
               maintenace (since the start of the maintenance task)

 deg_ub(i)     maximum extra power for processing unit i due to
               performance degradation
```

```
 deg_rate(i) degradation performance rate for processing unit i that
             belongs to ICBM(i)

 xip(i)      operating status of unit i just before the beginning of
             the current scheduling horizon

 dsp(i)      initial value of DS at the beggining of the prediction
             horizon

 omikron(i)  omikron(i)iB(i) = 25 omikron(i)$iT(i) = 45 -  max onload
             days of unit

 bigM(i,t)  large number (for recovery model)

 q_boil_min_t(i,t),q_boil_max_t(i,t),E_turb_min_t(i,t),E_turb_max_t(i,
 t), multiplier, E_turb_min_extreme_t(i,t),E_turb_max_extreme_t(i,t) ;

 psi(i)      =  4;

 psip(i)     =  0;

 omega(i)$iB(i) = 8; omega(i)$iT(i) = 16;

 omegap(i) = 0;

IFM('B8') = NO;  IFM('T6') = NO;

q_boil_min_t(i,t)$(K(i) AND PH(t)) = q_boil_min(i);

q_boil_max_t(i,t)$(K(i) AND PH(t)) = q_boil_max(i);

E_turb_min_t(i,t)$(K(i) AND PH(t)) = E_turb_min(i);

E_turb_max_t(i,t)$(K(i) AND PH(t)) = E_turb_max(i);

E_turb_min_extreme_t(i,t)$(iT(i) AND PH(t)) = E_turb_min_extreme(i);

E_turb_max_extreme_t(i,t)$(iT(i) AND PH(t)) = E_turb_max_extreme(i);

q_boil_min_t('B8',t)$(K('B8') AND PH(t) AND ORD(t)<(CARD(t)-30)) = 0;

q_boil_max_t('B8',t)$(K('B8') AND PH(t) AND ORD(t)<(CARD(t)-30)) = 0;

E_turb_min_t('T6',t)$(K('T6') AND PH(t) AND ORD(t)<(CARD(t)-30)) = 0;

E_turb_max_t('T6',t)$(K('T6') AND PH(t) AND ORD(t)<(CARD(t)-30)) = 0;

E_turb_min_extreme_t('T6',t)$(K('T6') AND PH(t) AND
ORD(t)<(CARD(t)30)) = 0;
```

```
E_turb_max_extreme_t('T6',t)$(K('T6') AND PH(t) AND
ORD(t)<(CARD(t)30)) = 0;

HEAT_UB('T6',t)$(K('T6') AND PH(t) AND ORD(t)<(CARD(t)-30)) = 0;

q_boil_min_t('B8',t)$(K('B8') AND PH(t) AND ORD(t) GE (CARD(t)-
30))=q_boil_min('B8')*0.8;

q_boil_max_t('B8',t)$(K('B8') AND PH(t) AND ORD(t) GE (CARD(t)-30)) =
q_boil_max('B8')*0.8;

E_turb_min_t('T6',t)$(K('T6') AND PH(t) AND ORD(t) GE (CARD(t)-30)) =
E_turb_min('T6')*0.5;

E_turb_max_t('T6',t)$(K('T6') AND PH(t) AND ORD(t) GE (CARD(t)-30)) =
E_turb_max('T6')*0.5;

E_turb_min_extreme_t('T6',t)$(K('T6') AND PH(t) AND ORD(t) GE
(CARD(t)-30)) = E_turb_min_extreme('T6')*0.5;

E_turb_max_extreme_t('T6',t)$(K('T6') AND PH(t) AND ORD(t) GE
(CARD(t)-30)) = E_turb_max_extreme('T6')*0.5;

HEAT_UB('T6',t)$(K('T6') AND PH(t) AND ORD(t) GE (CARD(t)-30)) =
HEAT_UB('T6',t)*0.5;

*=== typical maintenance

ni('B1') = 29;   main_cost('B1') = 4*5000;

ni('B2') = 25;   main_cost('B2') = 4*5000;

ni('B4') = 19;   main_cost('B4') = 4*5000;

ni('B6') = 31;   main_cost('B6') = 4*5000;

ni('B7') = 11;   main_cost('B7') = 4*5000;

*ni('B8') = 27;

ni('T1') = 20;   main_cost('T1') = 2*5000;

ni('T2') = 16;   main_cost('T2') = 2*5000;

*ni('T6') = 12;

*=== major maintenance

ni('T3') = 88;  main_cost('T3') =  8*5000;
```

```
ni('T5') = 41;  main_cost('T5') = 6*5000;
*=== major overhaul
ni('B3') = 88;   main_cost('B3') = 30*5000;
ni('B5') = 74;   main_cost('B5') = 30*5000;
ni('T4') = 11;   main_cost('T4') = 20*5000;
*=== typical maintenance
main_cost('B1') = 20000;
main_cost('B2') = 20000;
main_cost('B4') = 20000;
main_cost('B6') = 20000;
main_cost('B7') = 20000;
main_cost('T1') = 10000;
main_cost('T2') = 10000;
*=== major maintenance
main_cost('T3') = 41815;
main_cost('T5') = 30415;
*=== major overhaul
main_cost('B3') = 153729;
main_cost('B5') = 111966;
main_cost('T4') = 106269;
nip(i)  = 0;
tes(i)$(IFM(i))=85;     tls(i)$(IFM(i))=(290-ni(i));
deg_ub(i) = 1;
deg_rate(i) = 0.001 + 0.001$(effunit(i,'2')<0.9);
xip(i)      =  0;
dsp(i)      =  0;
```

```
omikron(i)$iB(i) = 25; omikron(i)$iT(i) = 45;

bigM(i,t)   = 1e6;

multiplier = 1;

SET ERROR(i,t);

ERROR(i,t)$((iT(i) AND errVAL(t)=0) AND
realprod(t,i)<E_turb_min_t(i,t)) = YES;

ERROR(i,t)$((iT(i) AND errVAL(t)=0) AND
realprod(t,i)>E_turb_max_t(i,t)) = YES;

ERROR(i,t)$((iB(i) AND errVAL(t)=0) AND
realprod(t,i)<q_boil_min_t(i,t)) = YES;

ERROR(i,t)$((iB(i) AND errVAL(t)=0) AND
realprod(t,i)>q_boil_max_t(i,t)) = YES;

DISPLAY ERROR;

*q_boil_min(i) = 0.45*q_boil_max(i);

*E_turb_min(i) = 0.50*E_turb_max(i);

*deg_rate('B8') = 0.001;  deg_rate('T6') = 0.001;

*$ONTEXT

BINARY VARIABLES

Y(i,t)

Ymin(i,t)

Ymax(i,t)

X(i,t)      is 1 if processing unit i is operating during time period
t

S(i,t)      is 1 if processing unit i starts up at the beginning of
time period t

F(i,t)      is 1 if processing unit i shuts down at the beginning of
time period t

W(i,t)      is 1 if a maintenace task starts in processing unit i at
the beginning of time period t;
```

```
POSITIVE VARIABLES

Q_BOIL_OUT(i,t)

Q_TURB_IN(i,t)   inlet heat in turbine i in time period t

R_up(i,t),R_d(i,t)

Q_TURB_OUT(i,t)   outlet heat from turbine i in time period t

E_TURB(i,t)       electricity generated from turbine i in time period t

E_BUY(t)    unsatisfied electricity demand in time period t

E_EXTRA(t)  extra electricity produced in time period t

H_BUY(j,t)  unsatisfied Heat demand in time period t

WasteHeat(j,t)    extra Heat produced in time period t

RCU(j,t)    Reduction-cooling unit $(TempOut(t)>-10)

DS(i,t)     cumulative time of the operation after the last offline maintenance of processing i at t

DW(i,t)     extra power consumed from processing unit i at time period t (indirectly related to energy-efficiency of the processing unit);

VARIABLES

OF    objective function (total cost);

EQUATIONS

QBOIL_LB,QBOIL_UB,

ETURB_LB,ETURB_UB

ZETURB_LB1,ZETURB_LB2,ZETURB_UB1,ZETURB_UB2,ZETURB_UB3,ZETURB_UB4,LinkYX

HEAT_UBT

BAL_steam

BAL_TURB1,

DEM_EL,DEM_DH
```

```
SF1,SF2,

SF3,SF4,S0,F0,MAX1,MAX2,MAIN_FL0,MAIN_FL1,MAIN_FL2,
DW1,DW2,DW3,RECM1,RECM2,RECM3,

OBJ;

*===========================pipeline transportation
problem=============

QBOIL_LB(i,t)$(K(i) AND iB(i) AND PH(t)).. Q_BOIL_OUT(i,t) =G=
q_boil_min_t(i,t)*X(i,t);

QBOIL_UB(i,t)$(K(i) AND iB(i) AND PH(t))..      Q_BOIL_OUT(i,t) =L=
q_boil_max_t(i,t)*X(i,t);

ETURB_LB(i,t)$(K(i) AND iT(i) AND PH(t))..      E_TURB(i,t) =G=
E_turb_min_extreme_t(i,t)*X(i,t);

ETURB_UB(i,t)$(K(i) AND iT(i) AND PH(t))..      E_TURB(i,t) =L=
E_turb_max_extreme_t(i,t)*X(i,t);

ZETURB_LB1(i,t)$(K(i) AND iT(i) AND PH(t))..    E_TURB(i,t) =L=
(E_turb_min_t(i,t)-0.001+10000*(1-Ymin(i,t));

ZETURB_LB2(i,t)$(K(i) AND iT(i) AND PH(t))..    E_TURB(i,t) =G=
E_turb_min_extreme_t(i,t)-10000*(1-Ymin(i,t));

ZETURB_UB1(i,t)$(K(i) AND iT(i) AND PH(t))..    E_TURB(i,t) =G=
(E_turb_max_t(i,t)+0.001)-10000*(1-Ymax(i,t));

ZETURB_UB2(i,t)$(K(i) AND iT(i) AND PH(t))..    E_TURB(i,t) =L=
E_turb_max_extreme_t(i,t)+10000*(1-Ymax(i,t));

ZETURB_UB3(i,t)$(K(i) AND iT(i) AND PH(t))..    E_TURB(i,t) =G=
E_turb_min_t(i,t)-10000*(1-Y(i,t));

ZETURB_UB4(i,t)$(K(i) AND iT(i) AND PH(t))..    E_TURB(i,t)=L=
E_turb_max_t(i,t)+10000*(1-Y(i,t));

LinkYX(i,t)$(K(i) AND iT(i) AND PH(t))..  Ymin(i,t)+Ymax(i,t)
+Y(i,t)=E=X(i,t);

HEAT_UBT(i,t)$(K(i) AND iT(i) AND PH(t))..      Q_TURB_OUT(i,t) =L=
HEAT_UB(i,t)*X(i,t);
```

```
BAL_steam(t)$PH(t)..    SUM(i$iB(i),(1-loss(i))*Q_BOIL_OUT(i,t))=E=
sum(i$iT(i),Q_TURB_IN(i,t))+SUM(j$KJ(j),RCU(j,t));

RCU.up(j,t)$PH(t)=0$(TempOut(t)>-10);

*====================================Energy balance===================

BAL_TURB1(i,t)$(K(i) AND iT(i) AND PH(t))..  Q_TURB_IN(i,t) =E=
E_TURB(i,t)/EffUnit(i,t)+Q_TURB_OUT(i,t);

DEM_EL(t)$PH(t).. SUM(i$(K(i) AND IT(i)), E_TURB(i,t)) + E_BUY(t) =E=
(1+own_use_el(t)*0)*el_dem(t)+E_EXTRA(t);

DEM_DH(j,t)$(PH(t) AND KJ(j))..     SUM(JI(j,i)$K(i), Q_TURB_OUT(i,t))
+ H_BUY(j,t)+0.9*RCU(j,t)=E=(1+own_use_ht(t))*heat_DH(j,t)+
WasteHeat(j,t);

*===============================Unit commitment/StartUp/Shut Down=====

SF1(i,t)$(K(i) AND PH(t))..   S(i,t) - F(i,t) =E= X(i,t)-
xip(i)$(ORD(t)=1)- X(i,t-1)$(ORD(t)>1) ;

SF2(i,t)$(K(i) AND PH(t))..   S(i,t) + F(i,t) =L= 1;

SF3(i,t)$(K(i) AND PH(t) AND omega(i)>1)..      X(i,t) =G=
SUM(tt$(PH(tt) AND ORD(tt) GE max(1,(ORD(t)-omega(i)+1)) AND ORD(tt)
LE ORD(t)),S(i,tt));


SF4(i,t)$(K(i) AND PH(t) AND psi(i)>1)..  1 - X(i,t) =G=
SUM(tt$(PH(tt) AND ORD(tt) GE max(1,(ORD(t)-psi(i)+1)) AND ORD(tt) LE
ORD(t)),F(i,tt));

S0(i,t)$(K(i) AND PH(t) AND (ORD(t) LE  (omega(i)-omegap(i))) AND
(omegap(i)>0 AND omegap(i)<omega(i)))..   X(i,t) =E= 1;

F0(i,t)$(K(i) AND PH(t) AND (ORD(t) LE  (psi(i)-psip(i))) AND
(psip(i)>0 AND psip(i)<psi(i))).. X(i,t) =E= 0;

=====================================================================

MAX1(i,t)$(K(i) AND PH(t))..     SUM(tt$(PH(tt) AND ORD(tt) GE
max(1,(ORD(t)-omikron(i))) AND ORD(tt) LE ORD(t)),X(i,tt)) =L=
omikron(i);
```

```
MAX2(i,t)$(K(i) AND PH(t) AND (ORD(t)=(omikron(i)-omegap(i)+1)) AND
(omegap(i)>1)).. SUM(tt$(PH(tt) AND ORD(tt) GE max(1,(ORD(t)-
(omikron(i)-omegap(i)))) AND ORD(tt) LE ORD(t)),X(i,tt))=L=
(omikron(i)-omegap(i));

*ongoing maintenance tasks from previous period

MAIN_FL0(i,t)$(K(i) AND PH(t) AND IDMp(i,t))..  X(i,t) =E= 0;

*flexible maintenance tasks

MAIN_FL1(i)$(K(i) AND IFM(i))..     SUM(t$(PH(t) AND (ORD(t) GE
tes(i)) AND (ORD(t) LE tls(i))), W(i,t)) =E= 1;

MAIN_FL2(i,t)$(K(i) AND PH(t) AND (ORD(t) GE tes(i)) AND (ORD(t) LE
(tls(i)+ni(i)-1)))..    X(i,t) + SUM(tt$(PH(tt) AND (ORD(tt) GE
max(tes(i),(ORD(t)-ni(i)+1))) AND (ORD(tt) LE
min(tls(i),ORD(t)))),W(i,tt)) =L= 1;

*condition-based maintenance

*=== Performance degradation and recovery model for processing units
===

DW1(i,t)$(K(i) AND PH(t) AND ICBM(i))..   DW(i,t) =L=
deg_ub(i)*X(i,t);

DW2(i,t)$(K(i) AND PH(t) AND ICBM(i))..   DW(i,t) =L=
deg_rate(i)*DS(i,t) + deg_ub(i)*(1-X(i,t));

DW3(i,t)$(K(i) AND PH(t) AND ICBM(i))..   DW(i,t) =G=
deg_rate(i)*DS(i,t) - deg_ub(i)*(1-X(i,t));

RECM1(i,t)$(K(i) AND PH(t) AND ICBM(i))..

DS(i,t) =L= bigM(i,t)*(1-W(i,t));


RECM2(i,t)$(K(i) AND PH(t) AND ICBM(i)).. DS(i,t) =G= (DS(i,t-
1)$(ORD(t)>1) + dsp(i)$(ORD(t)=1) + X(i,t)) - bigM(i,t)*W(i,t);

RECM3(i,t)$(K(i) AND PH(t) AND ICBM(i)).. DS(i,t) =L= (DS(i,t-
1)$(ORD(t)>1) + dsp(i)$(ORD(t)=1) + X(i,t)) + bigM(i,t)*W(i,t);

OBJ.. OF =E=
```

```
*start-up and shutdown costs for processing units

(SUM((i,t)$(K(i) AND PH(t)),((xi(i)*S(i,t)+(fi(i)*F(i,t)))))

*fixed operating costs for processing units

+SUM((i,t)$(K(i) AND PH(t)),(X(i,t)*fix_oper(i)))

*heat generation costs for boilers (coal cost)

+ SUM((i,t)$(K(i) AND
PH(t)),fuel_price*Q_BOIL_OUT(i,t)/(0.01*EffUnit(i,t)*CoalCalorific(t)*
GKaltoMWh))

*penalty cost from deviation from electricity demand

+ SUM(t$PH(t),(E_BUY(t)*penE + E_EXTRA(t)*penEex))

*penalty cost from deviation from Heat demand

+ SUM((t,j)$PH(t),(H_BUY(j,t)*penH + WasteHeat(j,t)*penHex))

*maintenance costs

+ SUM((i,t)$(K(i) AND PH(t) AND IFM(i)),(W(i,t)*main_cost(i)))

*cost for operating away from the ideak clean condition

+ SUM((i,t)$(K(i) AND PH(t) AND ICBM(i)), (DW(i,t)*pen_DW))

*penalty for extreme turbine regions

+ SUM((i,t)$(K(i) AND iT(i) AND PH(t)), ((Ymin(i,t) +
Ymax(i,t))*10000)))/multiplier ;

MODEL KUS_01 /

QBOIL_LB, QBOIL_UB,

ETURB_LB, ETURB_UB

ZETURB_LB1,ZETURB_LB2,ZETURB_UB1,ZETURB_UB2,ZETURB_UB3,ZETURB_UB4,Link
YX

HEAT_UBT

BAL_steam,

BAL_TURB1,
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```
DEM_EL, DEM_DH

SF1,SF2,

SF3,SF4,

MAIN_FL1,MAIN_FL2, DW1,DW2,DW3, RECM1,RECM2,RECM3,

OBJ/;

KUS_01.optfile = 1;

deg_ub(i)$iT(i) = 0.25*deg_ub(i);

DISPLAY ICBM,IFM,tes,tls,ni,deg_rate,deg_ub,
q_boil_min,q_boil_max,E_turb_min,E_turb_max,loss,dsp,
q_boil_min_t,q_boil_max_t,E_turb_min_t,E_turb_max_t ;

H_BUY.fx(j,t)=0;

tes(i)$(IFM(i))=1;     tls(i)$(IFM(i))=(CARD(t)-ni(i));

psi(i)      =  1;

omega(i)$iB(i) = 2; omega(i)$iT(i) = 2;

KUS_01.optfile=1;

SOLVE KUS_01 using MIP minimizing OF;

PARAMETERS

COST_SF(t),COST_FO(t),COST_BF(t),COST_MAIN(t),PEN_EBUY(t),
REAL_COST_T(t),REAL_COST, PEN_COST_T(t),PEN_Y(t),PEN_COST

PEN_EMOR(t),PEN_HBUY(t),PEN_HMOR(t),PEN_PERF(t)

TOTAL_COST_SF,TOTAL_COST_FO,TOTAL_COST_BF,TOTAL_COST_MAIN,
TOTAL_PEN_EBUY,TOTAL_PEN_EMOR,TOTAL_PEN_HBUY,TOTAL_PEN_HMOR,TOTAL_PEN_
PERF,TOTAL_PEN_Y

PER_SF,PER_FO,PER_BF,PER_MAIN; ;

*start-up and shutdown costs for processing units

COST_SF(t)$PH(t) =
SUM(i$K(i),((xi(i)*S.l(i,t)+(fi(i)*F.l(i,t)))))/multiplier;

*fixed operating costs for processing units
```

```
COST_FO(t)$PH(t) = SUM(i$K(i),(X.l(i,t)*fix_oper(i)))/multiplier;

*heat generation costs for boilers (coal cost)

COST_BF(t)$PH(t) =
SUM(i$K(i),fuel_price*Q_BOIL_OUT.l(i,t)/(0.01*EffUnit(i,t)*
CoalCalorific(t)*GKaltoMWh))/multiplier;

*maintenance costs

COST_MAIN(t)$PH(t)= SUM(i$(K(i) AND
IFM(i)),(W.l(i,t)*main_cost(i)))/multiplier;

*penalty cost from deviation from electricity demand

PEN_EBUY(t)$PH(t)= (E_BUY.l(t)*penE)/multiplier;

PEN_EMOR(t)$PH(t)= (E_EXTRA.l(t)*penEex)/multiplier;

*penalty cost from deviation from Heat demand

PEN_HBUY(t)$PH(t)= SUM(j,(H_BUY.l(j,t)*penH))/multiplier;

PEN_HMOR(t)$PH(t)= SUM(j,(WasteHeat.l(j,t)*penHex))/multiplier;

*penalty for operating away from the ideak clean condition

PEN_PERF(t)$PH(t)= SUM(i$(K(i) AND ICBM(i)),
(DW.l(i,t)*pen_DW))/multiplier;

*penalty for Y

PEN_Y(t)$PH(t)   = SUM(i$(K(i) AND iT(i)), (Ymin.l(i,t) +
Ymax.l(i,t)*1))/multiplier;

REAL_COST_T(t)$PH(t) = COST_SF(t) + COST_FO(t) + COST_BF(t) +
COST_MAIN(t);

REAL_COST = SUM((t)$PH(t),REAL_COST_T(t));

PEN_COST_T(t)$PH(t) = PEN_EBUY(t) + PEN_EMOR(t) + PEN_HBUY(t) +
PEN_HMOR(t) + PEN_PERF(t) + PEN_Y(t);

PEN_COST = SUM((t)$PH(t),PEN_COST_T(t));

TOTAL_COST_SF     = SUM((t)$PH(t),COST_SF(t));

TOTAL_COST_FO     = SUM((t)$PH(t),COST_FO(t));
```

```
TOTAL_COST_BF      = SUM((t)$PH(t),COST_BF(t));
TOTAL_COST_MAIN    = SUM((t)$PH(t),COST_MAIN(t));

TOTAL_PEN_EBUY     = SUM((t)$PH(t),PEN_EBUY(t));
TOTAL_PEN_EMOR     = SUM((t)$PH(t),PEN_EMOR(t));
TOTAL_PEN_HBUY     = SUM((t)$PH(t),PEN_HBUY(t));
TOTAL_PEN_HMOR     = SUM((t)$PH(t),PEN_HMOR(t));
TOTAL_PEN_PERF     = SUM((t)$PH(t),PEN_PERF(t));
TOTAL_PEN_Y        = SUM((t)$PH(t),PEN_Y(t));

PER_SF      = 100*TOTAL_COST_SF / REAL_COST;
PER_FO      = 100*TOTAL_COST_FO / REAL_COST;
PER_BF      = 100*TOTAL_COST_BF / REAL_COST;
PER_MAIN    = 100*TOTAL_COST_MAIN / REAL_COST;

DISPLAY  PER_SF,PER_FO,PER_BF,PER_MAIN,
TOTAL_COST_SF,TOTAL_COST_FO,TOTAL_COST_BF,TOTAL_COST_MAIN,
TOTAL_PEN_EBUY,TOTAL_PEN_EMOR,TOTAL_PEN_HBUY,TOTAL_PEN_HMOR,TOTAL_PEN_
PERF,TOTAL_PEN_Y;
CPUs = KUS_01.resusd;
DISPLAY  CPUs,E_BUY.l,H_BUY.l, E_EXTRA.l,WasteHeat.l,X.L,S.L,F.L,W.l;
PARAMETERS
SteamfromB
SteamtoT
CoalC(i,t)
MW(i,t),DMW(t)
H(i,t),HD
```

```
Ramp

Bsteam

iBsteam

iMW ;

CoalC(i,t)=Q_BOIL_OUT.l(i,t)/(EffUnit(i,"1")/100*CoalCalorific(t)*GKal
toMWh*0.001)/24;

Bsteam(i,t)$iB(i)=Q_BOIL_OUT.l(i,t)/24+eps;

MW(i,t)$iT(i)= E_TURB.l(i,t)/24+eps;

iBsteam(i,t)$iB(i)=round(24*Bsteam(i,t)/q_boil_max(i)$iB(i),2);

iMW(i,t)$iT(i)= round(24*MW(i,t)/E_turb_max(i)$iT(i),2);

DMW(t)=el_dem(t)/24;

H(i,t)$iT(i)=Q_TURB_OUT.l(i,t)/24+eps;

HD(t) = sum(j,heat_DH(j,t))/24;

DISPLAY     CPUs, i,Bsteam, PH,ICBM,IFM,tes,tls,E_BUY.l,H_BUY.l,
E_EXTRA.l,WasteHeat.lDMW ,MW,H,HD,CoalC,X.L,S.L,F.L,RCU.l, W.l,
DS.l,DW.l;

Execute_unload'Output.gdx',OF.l,Q_TURB_OUT.l,E_TURB.l,E_BUY.l,E_EXTRA.
l,H_BUY.l, WasteHeat.l,DMW
,MW,H,HD,CoalC,q_boil_min,q_boil_max,E_turb_min,E_turb_max,
xi,fi,fix_oper,main_cost, penH,penE, penEex,penHex,omega,omegap,
PH,ICBM,IFM,tes,tls,ni,deg_rate,deg_ub X.L,S.L,F.L,RCU.l,DS.l,DW.l,W.l

iBsteam,iMW;
```

A.2 Data for OPT-3

```
*$TITLE KUS CHP PLANT (KUS_01, SEQ=1)

SETS

i(*)  Main processing unit (boiler and turbines)      /B1*B8,T1*T6/

j(*)  pipelines (for district heating - DH)     /l1,l2/

t     time periods (from Excel)     /1*365/

m(*)  month /m1*m12/

iB(i) subset of boilers /B1*B8/

iT(i) subset of turbines      /T1*T6/

K(i)  set of processing units i included in the optimization

KJ(j) set of DH pipelines included in the optimization

PH(t) set of time periods included in the optimization

JI(j,i)     processing unit i connected to pipeline j

IFM(i)      set of processing unit i that are subject to flexible
time-window maintenance /B1*B8,T1*T6/

ICBM(i)     set of processing unit i that are subject to condition-
based maintenance

IDMp(i,t)   time periods t that processing unit is under maintenance
at the beginning of the planning horizon

B(*)  independent sets of boiler    /B1*B8/

Tu(*) independent sets of turbines  /T1*T6/

tempG(*)    General set of Temperatue for supply heat water for
heating relaited to TempOut(t)/Kond, 75deg,100deg,120deg/;

ALIAS (t,tt),(i,ii);

set

BT(B,Tu)    tuple subset for connections I_BOIL & I_TURB

Ti(Tu,i)    turbine set relation in general i unit sets
```

```
Bi(B,i)      Boiler  set relation in general i unit sets

TM(t,m)      days to month

TempC(tempG)       Commitment supply Temperatue -one of tempG

TTemp(t,TempG);

Bi(B,i) =yes$(ord(i)=ord(B)) ;

Ti(Tu,i) =yes$(ord(Tu)+8=ord(i));

PARAMETERS

Demdata(t,*)       demdata sheet from excel file

realprod(t,i)       real production maximum

WFIX(t,i)    units that are subject to fized time windows
maintenanceaximu

MaxMin(i,*) Uminimum and maximum extreme of unit capacity

MaxMinEX(i,*)      minimum and maximum extreme of unit capacity

el_dem(t)    electricity demand in time period t

heat_DH(j,t)       heat demand for DH pipeline j in time period t

q_boil_min(i)      minimum output Steam from boiler i [MWh per day]

q_boil_max(i)      maximum output Steam from boiler i [MWh per day]

E_turb_min(i)      minimum output Elc from turbine i [MWh per day]

E_turb_max(i)      maximum output Elc from turbine i [MWh per day]

E_turb_min_extreme(i)    minimum operating extreme for turbines

E_turb_max_extreme(i)    maximum operating extreme for turbines

Effdata(i,m)       efficiency of unit in month

EffUnit(i,t)       efficiency of unit in day

loss(i)      heat loss coefficient due to combustion loss/unburned fuel
             for 11 boiler units

HEAT_UBM(i,m)

HEAT_UB(i,t)
```

```
CoalCalorific(t)  Coal characteristics
own_use_ht(t)     own use heat in plant
own_use_el(t)     Elc for plant
TempOut(t)
QH(tempG,*)
QE(tempG,*)
main_cost(i)      maintenance cost
*costs
fi(i) shutdown cost for processing unit i
xi(i) startup cost for processing unit i
fix_oper(i) fixed operational cost KZT tenge
CPUs;
*==================== Import from Excel====================
$onecho > taskin.txt
$CALL GDXXRW.EXE data.xls @taskin.txt
*========================= import data from
GDX============================
$GDXIN data.gdx
$LOAD Demdata,realprod,WFIX,errVAL,MaxMinEX
$LOAD Effdata
$LOAD HEAT_UBM
$LOAD MaxMin
$GDXIN
*=====================================================================
====;
scalar
GKaltoMWh   convert GKal to MWh     /1.16223/
```

```
fuel_price  USD per tonn of Coal    /6/

pen_DW      Penalty for DW    /1e5/

penE  Penalty for BAY E       /1e5/

penH  Penalty for BAY H       /1e5/

penEex      Penalty  for extra E Energy   /1e2/

penHex      Penalty  for extra H Energy   /1e2/;

PH(t) =yes$(ord(t)<=365);

K(i)  =yes$(ord(i)<=14);

KJ(j) =yes$(ord(j)<=2);

JI('l1',i)=yes$(ord(i)>8 and ord(i)<=11);

JI('l2',i)=yes$(ord(i)>11);

TempOut(t) = Demdata(t,"TempOutM");

TTemp(t,tempG)$(TempOut(t)>0 and ord(tempG)=1)=yes;

TTemp(t,tempG)$(TempOut(t)<0 and TempOut(t)>-20 and ord(tempG)=3)=yes;

TTemp(t,tempG)$(TempOut(t)<-20  and ord(tempG)=4)=yes;

IDMp(i,t)  =yes$(ord(t)>10 and ord(t)<40);

TM(t,'m1')$(ord(t)<=31)=yes ;

TM(t,'m2')$(ord(t)>31  and ord(t)<=59)=yes ;

TM(t,'m3')$(ord(t)>59 and ord(t)<=90)=yes ;

TM(t,'m4')$(ord(t)>90 and ord(t)<=120)=yes ;

TM(t,'m5')$(ord(t)>120 and ord(t)<=151)=yes ;

TM(t,'m6')$(ord(t)>151 and ord(t)<=181)=yes ;

TM(t,'m7')$(ord(t)>181 and ord(t)<=211)=yes ;

TM(t,'m8')$(ord(t)>211 and ord(t)<=242)=yes ;

TM(t,'m9')$(ord(t)>242 and ord(t)<=273)=yes ;

TM(t,'m10')$(ord(t)>273 and ord(t)<=304)=yes ;
```

```
TM(t,'m11')$(ord(t)>304 and ord(t)<=334)=yes ;

TM(t,'m12')$(ord(t)>334 and ord(t)<=365)=yes;

el_dem(t)   = Demdata(t,"DemE") +Demdata(t,"OwnUseF");

heat_DH("l1",t)   = GKaltoMWh*Demdata(t,"DemH1");

heat_DH("l2",t)   = GKaltoMWh*Demdata(t,"DemH2");

own_use_el(t)     = Demdata(t,"OwnUse");

own_use_ht(t)           = 0.02;

loss(i)=0.02;

HEAT_UB(i,t)$iT(i)=sum(TM(t,m),HEAT_UBM(i,m));

q_boil_min(i)$iB(i) = MaxMin(i,'min');

q_boil_max(i)$iB(i) = MaxMin(i,'max');

E_turb_min(i)$iT(i) = MaxMin(i,'min');

E_turb_max(i)$iT(i) = MaxMin(i,'max');

E_turb_min_extreme(i)$iT(i)= MaxMinEX(i,'min');

E_turb_max_extreme(i)$iT(i)= MaxMinEX(i,'max');

EffUnit(i,t) = sum(TM(t,m),Effdata(i,m));

CoalCalorific(t) = 3980;

xi(i)  = (2*70*21+7*40+10)$iB(i) + (2*458)$iT(i);

fi(i) = (0.2*xi(i))$iB(i) + (0.5*xi(i))$iT(i);

fix_oper(i) = (5*40)$iB(i) + (3*40)$iT(i) ;

ICBM(i)=no;

realprod(t,i) = 24*realprod(t,i);

realprod(t,i)$iB(i) = GKaltoMWh*realprod(t,i)*0.595;

DISPLAY      t,PH,Demdata,MaxMin,K,KJ,JI,heat_DH,
el_dem,realprod,WFIX,errVAL

q_boil_min, q_boil_max
```

```
E_turb_min, E_turb_max, m,TM,EffUnit

xi,fi,TempG,TTemp,ifm,icbm;
```

A.3 Equation codes for optimized cases (OPT-1 and OPT-2)

```
EQUATIONS

QBOIL_LB,QBOIL_UB,

ETURB_LB,ETURB_UB

ZETURB_LB1,ZETURB_LB2,ZETURB_UB1,ZETURB_UB2,ZETURB_UB3,ZETURB_UB4,Link
YX

HEAT_UBT

BAL_steam

BAL_TURB1,

DEM_EL,DEM_DH

SF1,SF2,

SF3,SF4,S0,F0,MAX1,MAX2,MAIN_FL0,MAIN_FL1,MAIN_FL2,
DW1,DW2,DW3,RECM1,RECM2,RECM3,

OBJ;

*===============pipeline tranportation problem ============

QBOIL_LB(i,t)$(K(i) AND iB(i) AND PH(t).. Q_BOIL_OUT(i,t) =G=
q_boil_min_t(i,t)*X(i,t);

QBOIL_UB(i,t)$(K(i) AND iB(i) AND PH(t)).. Q_BOIL_OUT(i,t) =L=
q_boil_max_t(i,t)*X(i,t);

ETURB_LB(i,t)$(K(i) AND iT(i) AND PH(t)).. E_TURB(i,t) =G=
E_turb_min_extreme_t(i,t)*X(i,t);

ETURB_UB(i,t)$(K(i) AND iT(i) AND PH(t)).. E_TURB(i,t) =L=
E_turb_max_extreme_t(i,t)*X(i,t);

ZETURB_LB1(i,t)$(K(i) AND iT(i) AND PH(t)).. E_TURB(i,t) =L=
(E_turb_min_t(i,t)-0.001)+10000*(1-Ymin(i,t));

ZETURB_LB2(i,t)$(K(i) AND iT(i) AND PH(t)).. E_TURB(i,t) =G=
E_turb_min_extreme_t(i,t)-10000*(1-Ymin(i,t));

ZETURB_UB1(i,t)$(K(i) AND iT(i) AND PH(t)).. E_TURB(i,t) =G=
(E_turb_max_t(i,t)+0.001)-10000*(1-Ymax(i,t));
```

```
ZETURB_UB2(i,t)$(K(i) AND iT(i) AND PH(t)).. E_TURB(i,t) =L=
E_turb_max_extreme_t(i,t)+10000*(1-Ymax(i,t));

ZETURB_UB3(i,t)$(K(i) AND iT(i) AND PH(t)).. E_TURB(i,t) =G=
E_turb_min_t(i,t) - 10000*(1-Y(i,t));

ZETURB_UB4(i,t)$(K(i) AND iT(i) AND PH(t)).. E_TURB(i,t) =L=
E_turb_max_t(i,t)+10000*(1-Y(i,t));

LinkYX(i,t)$(K(i) AND iT(i) AND PH(t)).. Ymin(i,t) + Ymax(i,t)
+Y(i,t)=E=X(i,t);

HEAT_UBT(i,t)$(K(i) AND iT(i) AND PH(t)).. Q_TURB_OUT(i,t) =L=
HEAT_UB(i,t)*X(i,t);

BAL_steam(t)$PH(t)..   SUM(i$iB(i),(1-loss(i))*Q_BOIL_OUT(i,t)) =E=
sum(i$iT(i),Q_TURB_IN(i,t))+SUM(j$KJ(j),RCU(j,t));

RCU.up(j,t)$PH(t)=0$(TempOut(t)>-10);

*==========================Energybalance==============================

BAL_TURB1(i,t)$(K(i) AND iT(i) AND PH(t))..  Q_TURB_IN(i,t) =E=
E_TURB(i,t)/EffUnit(i,t)+Q_TURB_OUT(i,t);


DEM_EL(t)$PH(t).. SUM(i$(K(i) AND IT(i)), E_TURB(i,t)) +
E_BUY(t)=E=(1+own_use_el(t)*0)*el_dem(t)+E_EXTRA(t);

DEM_DH(j,t)$(PH(t) AND KJ(j)).. SUM(JI(j,i)$K(i), Q_TURB_OUT(i,t)) +
H_BUY(j,t)+0.9*RCU(j,t)=E=(1+own_use_ht(t))*heat_DH(j,t)+
WasteHeat(j,t);

*=============Unitcommitment/StartUp/ShutDown=========================

SF1(i,t)$(K(i) AND PH(t)).. S(i,t) - F(i,t) =E= X(i,t)-
xip(i)$(ORD(t)=1)-X(i,t-1)$(ORD(t)>1);

SF2(i,t)$(K(i) AND PH(t)).. S(i,t) + F(i,t) =L= 1;

SF3(i,t)$(K(i) AND PH(t) AND omega(i)>1).. X(i,t) =G= SUM(tt$(PH(tt)
AND ORD(tt) GE max(1,(ORD(t)-omega(i)+1)) AND ORD(tt) LE
ORD(t)),S(i,tt));
```

```
SF4(i,t)$(K(i) AND PH(t) AND psi(i)>1).. 1 - X(i,t) =G= SUM(tt$(PH(tt)
AND ORD(tt) GE max(1,(ORD(t)-psi(i)+1)) AND ORD(tt) LE
ORD(t)),F(i,tt));


S0(i,t)$(K(i) AND PH(t) AND (ORD(t) LE (omega(i)-omegap(i))) AND
(omegap(i)>0 AND omegap(i)<omega(i))).. X(i,t) =E= 1;

F0(i,t)$(K(i) AND PH(t) AND (ORD(t) LE (psi(i)-psip(i))) AND (psip(i)>0
ANDpsip(i)<psi(i)))..X(i,t)=E=0;

*=====================================================================

MAX1(i,t)$(K(i) AND PH(t)).. SUM(tt$(PH(tt) AND ORD(tt) GE
max(1,(ORD(t)-omikron(i))) AND ORD(tt) LE ORD(t)),X(i,tt)) =L=
omikron(i);

MAX2(i,t)$(K(i) AND PH(t) AND (ORD(t)=(omikron(i)-omegap(i)+1)) AND
(omegap(i)>1)).. SUM(tt$(PH(tt) AND ORD(tt) GE max(1,(ORD(t)-
(omikron(i)-omegap(i)))) AND ORD(tt) LE ORD(t)),X(i,tt))=L= (omikron(i)-
omegap(i));

*ongoing maintenance tasks from previous period

MAIN_FL0(i,t)$(K(i) AND PH(t) AND IDMp(i,t)).. X(i,t) =E= 0;

*flexible maintenance tasks

MAIN_FL1(i)$(K(i) AND IFM(i)).. SUM(t$(PH(t) AND (ORD(t) GE tes(i))
AND (ORD(t) LE tls(i))), W(i,t)) =E= 1;

MAIN_FL2(i,t)$(K(i) AND PH(t) AND (ORD(t) GE tes(i)) AND (ORD(t) LE
(tls(i)+ni(i)-1)))..X(i,t) + SUM(tt$(PH(tt) AND (ORD(tt) GE
max(tes(i),(ORD(t)-ni(i)+1))) AND (ORD(tt) LE
min(tls(i),ORD(t)))),W(i,tt))=L=1;

*========================condition-based-maintenance=================

*========Performance degradation and recovery model for processing
units===============================================================

DW1(i,t)$(K(i) AND PH(t) AND ICBM(i)).. DW(i,t) =L= deg_ub(i)*X(i,t);

DW2(i,t)$(K(i) AND PH(t) AND ICBM(i)).. DW(i,t) =L= deg_rate(i)*DS(i,t)
+deg_ub(i)*(1-X(i,t));
```

```
DW3(i,t)$(K(i) AND PH(t) AND ICBM(i)).. DW(i,t) =G= deg_rate(i)*DS(i,t)
-deg_ub(i)*(1-X(i,t));

RECM1(i,t)$(K(i)  AND  PH(t)  AND  ICBM(i))..  DS(i,t)  =L=  bigM(i,t)*(1-
W(i,t));

RECM2(i,t)$(K(i) AND PH(t) AND ICBM(i)).. DS(i,t) =G= (DS(i,t-
1)$(ORD(t)>1) + dsp(i)$(ORD(t)=1) + X(i,t)) - bigM(i,t)*W(i,t);

RECM3(i,t)$(K(i) AND PH(t) AND ICBM(i)).. DS(i,t) =L= (DS(i,t-
1)$(ORD(t)>1) + dsp(i)$(ORD(t)=1) + X(i,t)) + bigM(i,t)*W(i,t);

*======================losses for steam
transportation====================

*QBOIL_UB(B,t)$(PH(t))..       sum(BT(B,Tu),SteamSupply(B,Tu,t)) =l=
sum(Bi(B,i),q_boil_max(i)*X(i,t));

*DemandSteam(Tu,t)$(PH(t))..   sum(BT(B,Tu),SteamSupply(B,Tu,t)) =g=
sum(Ti(Tu,i),(E_TURB(i,t)/eff(i))+ Q_TURB_OUT(i,t));

**ramping  costs

*RampT(i,t)$(K(i) AND iT(i) AND PH(t) and ord(t)<>1)..
E_TURB(i,t)-E_TURB(i,t-1) =E= R_up(i,t) - R_d(i,t);

OBJ..OF =E=

*start-up and shutdown costs for processing units

(SUM((i,t)$(K(i)ANDPH(t)),((xi(i)*S(i,t)+(fi(i)*F(i,t)))))

*fixed operating costs for processing units

 +SUM((i,t)$(K(i)ANDPH(t)),(X(i,t)*fix_oper(i)))

*heat generation costs for boilers (coal cost) + SUM((i,t)$(K(i) AND
PH(t)),fuel_price*Q_BOIL_OUT(i,t)/(0.01*EffUnit(i,t)*CoalCalorific(t)*
GKaltoMWh))

*penalty cost from deviation from electricity demand

 +SUM(t$PH(t),(E_BUY(t)*penE + E_EXTRA(t)*penEex))

*penalty cost from deviation from Heat demand

+SUM((t,j)$PH(t),(H_BUY(j,t)*penH + WasteHeat(j,t)*penHex))
```

```
*maintenance costs
+ SUM((i,t)$(K(i) AND PH(t) AND IFM(i)),(W(i,t)*main_cost(i)))
*cost for operating away from the ideak clean condition +
SUM((i,t)$(K(i) AND PH(t) AND ICBM(i)), (DW(i,t)*pen_DW))
*penalty for extreme turbine regions
+ SUM((i,t)$(K(i) AND iT(i) AND PH(t)), ((Ymin(i,t) +
Ymax(i,t))*10000))
)/multiplier ;
MODEL KUS_01 /
QBOIL_LB, QBOIL_UB,
ETURB_LB, ETURB_UB
ZETURB_LB1,ZETURB_LB2,ZETURB_UB1,ZETURB_UB2,ZETURB_UB3,ZETURB_UB4,Link
YX
HEAT_UBT
BAL_steam,
BAL_TURB1,
DEM_EL,DEM_DH
SF1,SF2,
SF3,SF4,
MAIN_FL1,MAIN_FL2,DW1,DW2,DW3,RECM1,RECM2,RECM3,
OBJ/;
KUS_01.optfile=1;
deg_ub(i)$iT(i)=0.25*deg_ub(i);
DISPLAYICBM,IFM,tes,tls,ni,deg_rate,deg_ub,
q_boil_min,q_boil_max,E_turb_min,E_turb_max,loss,dsp, H_BUY.fx(j,t)=0;
tes(i)$(IFM(i))=1; tls(i)$(IFM(i))=365;
psi(i)  =  1;
```

```
omega(i)$iB(i) = 2; omega(i)$iT(i) = 2;

PARAMETER help(i);

help(i) = SUM(t,WFIX(t,i)*ORD(t));

W.fx(i,t)$(ORD(t)<(help(i)-30) OR ORD(t)>(help(i)+30)) = 0;

KUS_01.optfile=1;

SOLVE KUS_01 using MIP minimizing OF;

PARAMETERS

COST_SF(t),COST_FO(t),COST_BF(t),COST_MAIN(t),PEN_EBUY(t),
REAL_COST_T(t),REAL_COST, PEN_COST_T(t),PEN_Y(t),PEN_COST

PEN_EMOR(t),PEN_HBUY(t),PEN_HMOR(t),PEN_PERF(t)

TOTAL_COST_SF,TOTAL_COST_FO,TOTAL_COST_BF,TOTAL_COST_MAIN,
TOTAL_PEN_EBUY,TOTAL_PEN_EMOR,TOTAL_PEN_HBUY,TOTAL_PEN_HMOR,TOTAL_PEN_
PERF,TOTAL_PEN_Y

PER_SF,PER_FO,PER_BF,PER_MAIN; ;

*start-up and shutdown costs for processing units

COST_SF(t)$PH(t) =
SUM(i$K(i),((xi(i)*S.l(i,t)+(fi(i)*F.l(i,t)))))/multiplier;

*fixed operating costs for processing units

COST_FO(t)$PH(t) = SUM(i$K(i),(X.l(i,t)*fix_oper(i)))/multiplier;

*heat generation costs for boilers (coal cost)

COST_BF(t)$PH

(t) = SUM(i$K(i),fuel_price*Q_BOIL_OUT.l(i,t)/(0.01*EffUnit(i,t)*
CoalCalorific(t)*GKaltoMWh))/multiplier;

*maintenance costs

COST_MAIN(t)$PH(t)= SUM(i$(K(i) AND
IFM(i)),(W.l(i,t)*main_cost(i)))/multiplier;

*penalty cost from deviation from electricity demand

PEN_EBUY(t)$PH(t)= (E_BUY.l(t)*penE)/multiplier;
```

```
PEN_EMOR(t)$PH(t)= (E_EXTRA.l(t)*penEex)/multiplier;

*penalty cost from deviation from Heat demand

PEN_HBUY(t)$PH(t)= SUM(j,(H_BUY.l(j,t)*penH))/multiplier;

PEN_HMOR(t)$PH(t)= SUM(j,(WasteHeat.l(j,t)*penHex))/multiplier;

*penalty for operating away from the ideak clean condition

PEN_PERF(t)$PH(t)= SUM(i$(K(i) AND ICBM(i)),
(DW.l(i,t)*pen_DW))/multiplier;

*penalty for Y

PEN_Y(t)$PH(t)   = SUM(i$(K(i) AND iT(i)), (Ymin.l(i,t) +
Ymax.l(i,t)*1))/multiplier;

REAL_COST_T(t)$PH(t) = COST_SF(t) + COST_FO(t) + COST_BF(t) +
COST_MAIN(t);

REAL_COST = SUM((t)$PH(t),REAL_COST_T(t));

PEN_COST_T(t)$PH(t) = PEN_EBUY(t) + PEN_EMOR(t) + PEN_HBUY(t) +
PEN_HMOR(t) + PEN_PERF(t) + PEN_Y(t);

PEN_COST=SUM((t)$PH(t),PEN_COST_T(t));

TOTAL_COST_SF=SUM((t)$PH(t),COST_SF(t));

TOTAL_COST_FO=SUM((t)$PH(t),COST_FO(t));

TOTAL_COST_BF=SUM((t)$PH(t),COST_BF(t));

TOTAL_COST_MAIN=SUM((t)$PH(t),COST_MAIN(t));

TOTAL_PEN_EBUY=SUM((t)$PH(t),PEN_EBUY(t));

TOTAL_PEN_EMOR=SUM((t)$PH(t),PEN_EMOR(t));

TOTAL_PEN_HBUY=SUM((t)$PH(t),PEN_HBUY(t));

TOTAL_PEN_HMOR=SUM((t)$PH(t),PEN_HMOR(t));

TOTAL_PEN_PERF=SUM((t)$PH(t),PEN_PERF(t));

TOTAL_PEN_Y=SUM((t)$PH(t),PEN_Y(t));

PER_SF=100*TOTAL_COST_SF/REAL_COST;
```

```
PER_FO=100*TOTAL_COST_FO/REAL_COST;

PER_BF=100*TOTAL_COST_BF/REAL_COST;

PER_MAIN=100*TOTAL_COST_MAIN/REAL_COST;

DISPLAY PER_SF,PER_FO,PER_BF,PER_MAIN,
TOTAL_COST_SF,TOTAL_COST_FO,TOTAL_COST_BF,TOTAL_COST_MAIN,
TOTAL_PEN_EBUY,TOTAL_PEN_EMOR,TOTAL_PEN_HBUY,TOTAL_PEN_HMOR,TOTAL_PEN_
PERF,TOTAL_PEN_Y;

CPUs=KUS_01.resusd;

DISPLAYCPUs,E_BUY.l,H_BUY.l,E_EXTRA.l,WasteHeat.l,X.L,S.L,F.L,W.l;

PARAMETERS

SteamfromB

SteamtoT

CoalC(i,t)

MW(i,t),DMW(t)

H(i,t),HD

Ramp

Bsteam

iBsteam

iMW;

CoalC(i,t)=Q_BOIL_OUT.l(i,t)/(EffUnit(i,"1")/100*CoalCalorific(t)*GKal
toMWh*0.001)/24;

Bsteam(i,t)$iB(i)=Q_BOIL_OUT.l(i,t)/24+eps;

MW(i,t)$iT(i)=E_TURB.l(i,t)/24+eps;

iBsteam(i,t)$iB(i)=round(24*Bsteam(i,t)/q_boil_max(i)$iB(i),2);

iMW(i,t)$iT(i)=round(24*MW(i,t)/E_turb_max(i)$iT(i),2);

DMW(t)=el_dem(t)/24;

H(i,t)$iT(i)=Q_TURB_OUT.l(i,t)/24+eps;
```

```
HD(t)=sum(j,heat_DH(j,t))/24;

 DISPLAYCPUs,i,Bsteam,PH,ICBM,IFM,tes,tls,E_BUY.l,H_BUY.l,
E_EXTRA.l,WasteHeat.l,DMW,MW,H,HD,CoalC,X.L,S.L,F.L,RCU.l,W.l,
DS.l,DW.l;

Execute_unload'Output.gdx',
OF.l,Q_TURB_OUT.l,E_TURB.l,E_BUY.l,E_EXTRA.l,H_BUY.l,   WasteHeat.l,DMW
,MW,H,HD,CoalC,q_boil_min,q_boil_max,E_turb_min,E_turb_max,xi,fi,fix_o
per,main_cost,penH,penE,penEex,penHex,omega,omegap,PH,ICBM,IFM,tes,tls
,ni,deg_rate,deg_ub,X.L,S.L,F.L,RCU.l,DS.l,DW.l,W.l,iBsteam,iMW ;
```

Appendix B

B.1 Gams illustration for the case study of co-firing biomass with coal using the state task network (STN) approach

```
*OLUWATOSIN MURELE

* A General Representation for Modeling Operations in Energy Supply
Chains

OPTION      MIP = CPLEX,      RESLIM = 1000000000,    ITERLIM =
1000000000;

OPTION      OPTCR = 0.00,     LIMROW = 1e8,     LIMCOL=1e8;

SETS

p     tasks(conversion &transfer)

q     technologies (conversion & pre-processing & transfer & storage)

s     states (energy material resources & energy forms & pollutants)

t     time periods

r     regions ;

ALIAS (r,rr),(t,tt);

SETS

R_in(r)     regions r that are part of the local (internal) energy
network

S_U(s)      states that have demand in region r (represented as demand
for useful products states)

S_rm(s)     states s that are considered as raw materials

S_G(s)      states s that can be stored

S_G_lim(s)  capacity of storage states s

Q_C(q)      conversion technologies q

Q_TR(q)     transfer technologies q

Q_G(q)      storage technologies q
```

```
Q_E(q)       local exploitation technology q (imaginary tranfer of
             locally available state with the same region r)

PS_in(p,s)   input states s to task p

PS_out(p,s)  output states s to task p

IS_rm(p,s)   input local available states s (raw materials) to task p

IS_T(p,s)    tranfer task p for state s

QP(q,p)      technologies q that can perform task p

QS(q,s)      technologies q that involve state s

QR(q,r)      technologies q that can be installed in region r

SR(s,r)      states s for which a task can take place in region r

RR_t(r,rr)   available state flows from region r to regions rr

TIP_t(t)     time periods

S_UNDESIRED(s)    undesired state

S_DISP(r,s)       disposed state

S_rm_nonrenew(s)  Nonrenewable raw material state

S_rm_renew(s)     Renewable material state ;

PARAMETERS

alpha_min(r,rr,p,q,t)   minimum availability percentage of output
state s from task p [PS_out(ps)] using technology q between regions r
rr

alpha_max(r,rr,p,q,t)   maximum availability percentage of output
state s from task p [PS_out(ps)] using technology q between zones r
and rr

beta_min(r,s,t)   minimum inventory level of state S_G in region r in
time period t

beta_max(r,s,t)   maximum inventory level of state S_G in region r in
time period t

gamma_min(r,q,t)  minimum capacity of technology q whose installation
can start in r in time period t
```

gamma_max(r,q,t)	maximum capacity of technology q whose installation can start in r in time period t
delta(r,q,t)	fixed operating cost for the total installed capacities of technology q
epsilon(r,q,t)	investment required (per unit) for increasing the capacity of technology q in region r in time period t
epsilon0(r,q,t)	initial investment cost required to establish a technology
zeta(r,q,t)	demand for useful product state in region r in time period t
eta(r,s,t)	co-efficient for deterioration of states that can be stored
kappa_in(s,p,q)	coefficient for input state s of task p [PS_in(ps)] performed from technology q of region r in time period t
kappa_out(s,p,q)	coefficient for output state s of task p [PS_out(ps)] performed from tech q of region r in time period t
lambda(r,s,t)	coefficient of holding cost for storable states
mu(r,q,t)	Time for installation for technology q in region r or the duration of constructing an additional facility for an implementation start in period t
omega(r,s,t)	maximum avalaible amount of state S_rm in region r in time period t
omega_renew(r,s,t)	maximum available amount of renewable state in region r in time period t
omega_nonrenew (r,s,t)	maximum available amount of nonrenewable state in region r in time period t
ppi(r,s,r,q,t)	cost of states production through conversion technology
psi_r(r,s,p,q,t)	cost of raw materials
psi_rt(rr,r,s,p,q,t)	cost of transfer for state s through technology q from region rr to r both in the R_in

```
psi(rr,r,s,p,q,t) purchase of raw material state from regions outside
of R_in

c0(r,q)     initial installed capacity of technology q in region r (in
t=0)

g0(r,s)     initial available inventory of state s in region r (in
t=0)

ex(rr,r,s,p,q,t)  purchase of useful product state from external
region r

ff0(r,rr,q),cg0(r,s,j),lambda_disp(r,s,t), mu_t(r,rr,q,t);

$include ICCE_TEST3
```

BINARY VARIABLES

V(r,q,t) equals to 1 if biomass exploitation, pre-processing and conversion technologies q are established for the first time in region r at time period t, zero if otherwise.

VG (r,s,q,t) equals to 1 if storage technology q for state s is established for the first time in region r at time period t, zero if otherwise.

Z(r,q,t) equals to 1 if capacity of biomass exploitation, pre-processing and conversion technology q begins installing in region r in time period t, zero if otherwise.

Z_TR(r,rr,j,t) equals to 1 if capacity of transfer technology q starts installing in region r in time period t, zero if otherwise.

ZG(r,s,q,t) equals to 1 if capacity of storage technology q begins installing in region rin time period t, zero if otherwise.

POSITIVE VARIABLES

M(r,rr,p,q,t) squantity of material state s converted or transferred by task p using q from region r to region rr in time period t

G(r,s,t)	stock of state that remain in region r at the end of time period t
C(r,j,t)	overall capacity of storage technology q that can store states in region r at time interval t
C_TR(r,rr,q,t)	overall capacity of transfer technology q that can transfer state from one region to another
E(r,q,t)	increase of capacity for technology j in r in time period t
E_TR(r,rr,q,t)	capacity increase of transfer technology that can transfer state from one region to another
CG(r,s,q,t)	overall capacity of storage technology q that can store state in region r
EG(r,s,q,t)	capacity increase of storage technology

```
DISPOSED(r,s,t)   disposed state

FAC(t)      fixed assets cost in time period t

FOC(t)      fixed operating cost in time period t

VOC(t)      variable operating cost in time period t

IC(t)       inventory cost for material states in time period t

HC(t)       production cost for useful product states in time period t

CM(t)       cost of raw materials states

CM1(t)      cost of exploitation use for local raw material states
            available in each region r

CM2(t)      transportation cost for raw materials states within R_in

CM3(t)      cost of raw materials purchase from regions outside R_in

TRC(t)            transfer cost for final product states within
            internal regions and external sales of useful product
            states to external regions

C_TR(t)     overall capacity of transfer technology q

DC(t)       cost of disposing unwanted states to the environment
(penalty)

N(r,s,t)    quantity of states with unmet demand

NS(t)       penalty (cost) for no-sales, ie unmet demands

INFEASIBLE(z,s,t);

VARIABLE

OF    objective function (total cost);
```

B.2 Equation codes for co-firing biomass with coal

```
EQUATIONS EQ1,EQ2a,EQ2b, EQB1,EQB2a,EQB2b, EQt1,EQ2ta,EQ2tb,
EQ3pa,EQ3pb,EQ3ta,EQ3tb,EQ4a,EQ4b, EQ5,EQ6,EQ7, EQ8,EQ8B,EQ9,
EQ9B,EQ10, EQ10B,EQ11,EQ11t,EQ11B,EQ12, EQ13,EQ14,EQ15,EQ15b,
EQ16,EQ17,EQ18,EQ19,EQ20, EQ21;

*======================================= D E S I G
N=======================

EQ1(r,q,t) $(TIP_t(t) AND R_in(r) and QR(q,r) and not (Q_TR(q) or
Q_G(q))).. C(r,q,t) =e= C(r,q,t-1)$(ord(t)>1) + c0(r,q)$(ord(t)=1) +
E(r,q,t);

EQ2a(r,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and not (Q_TR(q) or
Q_G(q))).. E(r,q,t) =g= gamma_min(r,q,t)*R(r,q,t-mu(r,q,t));

EQ2b(r,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and not (Q_TR(q) or
Q_G(q))).. E(r,q,t) =l= gamma_max(r,q,t)*Z(r,q,t-mu(r,q,t));

EQB1(r,s,q,t) $(TIP_t(t) AND R_in(r) and QR(q,r) and SR(s,r) and
Q_G(q) AND QS(q,s) AND S_G_lim(s)).. CG(r,s,q,t) =e= CG(r,s,q,t-
1)$(ord(t)>1) + cg0(r,s,q)$(ord(t)=1) + EG(r,s,q,t);

EQB2a(r,s,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and SR(s,r) and
Q_G(q) AND QS(q,s) AND S_G_lim(s)).. EG(z,s,j,t) =g=
gamma_min(r,q,t)*ZG(r,s,q,t-mu(r,q,t));

EQB2b(r,s,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and SR(s,r) and Q_G(q)
AND QS(q,s)AND S_G_lim(s)).. EG(r,s,q,t) =l=
gamma_max(r,q,t)*ZG(r,s,q,t-mu(r,q,t));

EQt1(r,rr,q,t) $(TIP_t(t) AND R_in(r) and QR(q,r) and QR(q,rr) and
Q_TR(q) and RR_t(r,rr)).. C_TR(r,rr,q,t) =e= C_TR(r,rr,q,t-
1)$(ord(t)>1) + cc0(z,zz,j)$(ord(t)=1) + E_TR(r,rr,q,t);

EQ2ta(r,rr,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and QR(q,rr) and
Q_TR(q) and RR_t(r,rr)).. E_TR(r,rr,q,t) =g=
gamma_min(r,q,t)*Z_TR(r,rr,q,t-mu_t(r,rr,q,t));

EQ2tb(r,rr,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and QR(q,rr) and
Q_TR(q) and RR_t(r,rr)).. E_TR(r,rr,q,t) =l=
gamma_max(r,q,t)*Z_TR(r,rr,q,t-mu_t(r,rr,q,t));
```

```
======================== L I N K D E S I G N - P L A N N I N G =========

EQ3pa(r,p,q,t)$(TIP_t(t) AND (Q_C(q) OR Q_E(j)) and R_in(r) and QP(q,p)
and QR(q,r)).. M(z,z,i,j,t) =g= alpha_min(z,z,i,j,t)*F(z,j,t);

EQ3pb(z,i,j,t)$(TIP_t(t) AND (J_C(j) OR J_E(j)) and Z_in(z) and JI(j,i)
and JZ(j,z)).. P(r,r,p,q,t) =l= alpha_max(r,r,p,q,t)*C(z,j,t);

EQ3ta(r,rr,p,q,t)$(TIP_t(t) AND Q_TR(q) and QP(q,p) and QR(q,r) and
QR(q,rr) and RR_t(r,rr)).. M(r,rr,p,q,t) =g=
alpha_min(r,rr,p,q,t)*C_TR(r,rr,q,t);

EQ3tb(r,rr,p,q,t)$(TIP_t(t) AND Q_TR(q) and QP(q,p) and QR(q,r) and
QR(q,rr) and RR_t(r,rr)).. M(r,rr,p,q,t) =l=
alpha_max(r,rr,p,q,t)*C_TR(r,rr,q,t);

EQ4a(r,s,t)$(TIP_t(t) AND S_G_lim(s) and R_in(r) and SR(s,r)).. G(r,s,t)
=g= beta_min(r,s,t)*SUM(q$(QR(q,r) and Q_G(q) and QS(q,s)),
CG(r,s,q,t));

EQ4b(r,s,t)$(TIP_t(t) AND S_G_lim(s) and R_in(r) and SR(s,r)).. G(r,s,t)
=l= beta_max(r,s,t)*SUM(q$(QR(q,r) and Q_G(q) and QS(q,s)),
CG(r,s,q,t));

*=================================== P L A N N I N G
=====================

EQ5(r,s,t)$(TIP_t(t) and SR(s,r) AND S_rm(s) AND NOT
S_rm_nonrenew(s))..SUM((p,q)$(Q_E(q) and R_in(r) and PS_rm(p,s) and
QP(q,p) and QR(q,r)),Q(r,r,p,q,t)) + SUM((rr,p,q)$(Q_TR(q) and
SR(s,rr) and QP(q,p) and PS_T(i,s) and QR(q,r) and QR(q,rr) and
RR_t(r,rr)), M(r,rr,p,q,t)) =l= omega(r,s,t);

EQ6(r,s)$(S_rm(s) AND S_rm_nonrenew(s) and SR(s,r))..
SUM((p,q,t)$(TIP_t(t) AND Q_E(q) and R_in(r) and PS_rm(p,s) and
QP(q,p) and QR(q,r)),M(r,r,p,q,t)) =l= SUM(t$(ORD(t)=1),omega(r,s,t));

EQ7(r,s,t)$(TIP_t(t) and SR(s,r)).. G(r,s,t)$S_G(s) =e=
g0(r,s)$(S_B(s) and ord(t)=1) + (1-eta(r,s,t))*G(r,s,t-1)$(S_G(s) AND
ord(t)>1) + SUM((rr,p,q)$(Q_TR(q) and PS_T(p,s) and QR(q,r) and
QR(q,rr) and QP(q,p) and rr_t(rr,r)), kappa_out(s,p,q)*M(rr,r,p,q,t))-
SUM((rr,p,q)$(Q_TR(q) and PS_T(p,s) and QR(q,r) and QR(q,rr) and
QP(q,p) and RR_t(r,rr)), kappa_in(s,p,q)*M(r,rr,p,q,t))+
SUM((p,q)$(Q_C(q) and PS_out(p,s) and QR(q,r) and QP(q,p)),
```

```
kappa_out(s,p,q)*M(r,r,p,q,t))- SUM((p,q)$(Q_C(q) and PS_in(p,s) and
QR(q,r) and QP(q,p)),  kappa_in(s,p,q)*M(r,r,p,q,t)) - zeta(r,s,t) -
DISPOSED(r,s,t)$S_DISP(r,s)+INFEASIBLE(r,s,t)$(zeta(r,s,t)>0)+
SUM((p,q)$(Q_E(q) and PS_rm(p,s) and QR(j,z) and QP(q,p)),
M(r,r,p,q,t));
```

```
*==================================== E C O N O M I C
======================

EQ8(r,q)$(R_in(r) and QR(q,r) and not (Q_TR(q) or Q_G(q)))..
SUM(t$(TIP_t(t)), V(r,q,t)) =l= 1;

EQ9(r,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and not (Q_TR(q) or
Q_B(q))).. V(r,q,t) =l= Z(r,q,t);

EQ10(r,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and not (Q_TR(q) or
Q_G(q))).. V(r,q,t) =g= Z(r,q,t) - SUM(tt$(ord(tt) < ord(t)),
V(r,q,tt));

EQ8B(r,s,q)$(R_in(r) and QR(q,r) and QS(q,s) and Q_G(q))..
SUM(t$(TIP_t(t)), VG(r,s,q,t)) =l= 1;

EQ9B(r,s,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and QS(q,s) and
Q_G(q))..       VG(r,s,q,t) =l= ZG(r,s,q,t);

EQ10B(r,s,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and QS(q,s) and
Q_G(q))..      VG(r,s,q,t) =g= ZG(r,s,q,t) - SUM(tt$(ord(tt) < ord(t)),
VG(r,s,q,tt));

EQ11(t)$TIP_t(t)..    FAC(t) =e= SUM((r,q)$(R_in(r) and QR(q,r) and not
(Q_TR(q) or Q_G(q))), epsilon0(r,q,t)*V(r,q,t) +
epsilon(r,q,t)*E(r,q,t))+ SUM((r,s,j)$(R_in(r) and QR(q,r) and QS(q,s)
and not (Q_TR(q) or Q_E(q) or Q_C(q))),epsilon0(r,q,t)*VG(r,s,q,t) +
epsilon(r,q,t)*EG(r,s,q,t));

* investment for transfer network

EQ11t(t)$TIP_t(t)..       CT(t) =e= SUM((r,rr,q)$(TIP_t(t) AND R_in(r)
AND QR(q,r) and QR(q,rr) and Q_TR(q) and RR_t(r,rr)),
epsilon(r,q,t)*E_TR(r,rr,q,t) + epsilon0(r,q,t)*YT(r,rr,q,t));

EQ11B(t)$TIP_t(t)..      GT(t) =E= SUM((r,s,q)$(R_in(r) and QR(q,r) and
SR(s,r) and Q_G(q) AND QS(q,s)), epsilon(r,q,t)*EG(r,s,q,t));

EQ12(t)$TIP_t(t)..      FAC_TR(t) =e= SUM((r,q)$(R_in(r) and QR(q,r) and
not (Q_TR(q) or Q_G(q))), delta(r,q,t)*C(r,q,t));

EQ13(t)$TIP_t(t).. VOC(t) =e= CM(t) + HC(t) + IC(t) - TRC(t) + DC(t)+
NS(t);
```

```
*EQ14(t)$TIP_t(t).. HC(t) =e= SUM((r,s,p,q)$(R_in(r) and Q_C(q) and
SR(s,r) and PS_out(p,s) and QR(q,r) and Q_P(q,p)),
ppi(z,s,i,j,t)*P(z,z,i,j,t));

EQ15(t)$TIP_t(t).. IC(t) =e= SUM((r,s)$(R_in(r) and S_G(s) and SR(s,r)),
lambda(r,s,t)*G(r,s,t));

EQ15b(t)$TIP_t(t).. DC(t) =e= SUM((r,s)$(R_in(r) and S_DISP(r,s) and
SR(s,r)), lambda_disp(r,s,t)*DISPOSED(r,s,t));

*EQ16(t)$TIP_t(t).. CM1(t) =e= SUM((r,s,p,q)$(R_in(r) and S_rm(s) and
SR(s,r) and QS(q,s) and QP(q,p) and QR(q,r) and Q_E(q) and PS_rm(p,s)),
psi_r(r,s,p,q,t)*M(r,r,p,q,t));

EQ17(t)$TIP_t(t).. CM2(t) =e= SUM((r,rr,s,p,q)$(R_in(r) and R_in(rr)
and S_rm(s) and SR(s,r) and SR(s,rr) and QS(q,s) and QP(q,p) and
ord(rr) ne ord(r)and QR(q,r) and QR(q,rr) and Q_TR(q) and PS_T(p,s)
and RR_t(r,rr)), psi_rt(r,rr,s,p,q,t)*M(r,rr,p,q,t));

EQ18(t)$TIP_t(t).. CM3(t) =e= SUM((rr,r,s,p,q)$(not R_in(rr) and
R_in(r) and S_rm(s) and SR(s,r) and SR(s,rr) and QR(q,r) and QR(q,rr)
and QS(q,s) and QP(q,p)and Q_TR(q) and PS_T(p,s) and RR_t(rr,r)),
psi(rr,s,p,q,t)*M(rr,r,p,q,t));

EQ19(t)$TIP_t(t).. CM(t) =e= CM1(t) + CM2(t) + CM3(t);

EQ20(t)$TIP_t(t).. TRC(t) =e= SUM((rr,r,s,p,q)$(R_in(rr) and
RR_t(rr,z) and S_U(s) and SR(s,r) and SR(s,rr)and QR(q,r) and QR(q,rr)
and QS(q,s) and QP(q,p) and Q_TR(q) and PS_T(p,s)),
ex(rr,r,s,p,q,t)*M(rr,r,p,q ,t));

EQ21..OF =e= SUM (t$TIP_t(t), FAC(t) + TRC(t) + FOC(t) + VOC(t))+ SUM
((r,s,t)$(TIP_t(t) AND zeta(r,s,t)>0), 100000*INFEASIBLE(r,s,t));

MODEL    STN_MODEL /ALL/;
```

B.3 GAMS data codes for biomass co-firing with coal

```
SETS
p     /p01*p07/
q     /q01*q11,q-s01, q-s08,q-s02_1,q-s02_2,q-s03,q-s06/
s     /s01*s08/
t     /t01*t20/
r     /r01*r03/ ;
ALIAS (r,rr),(t,tt) ;
SETS
R_in(r),S_u(s),S_rm(s),S_G(s),SR(s,r),
Q_C(q),Q_TR(q),Q_G(q), QP(q,p),QS(q,s),QR(q,r),
PS_in(p,s),PS_out(p,s),PS_T(p,s),Q_E(q),PS_rm(p,s),
RR_t(r,rr),R_ex(r),TIP_t(t)
S_UNDESIRED(s),S_DISP(r,s);
 TIP_t(t)$(ord(t) le 20) = YES;
*internal zones*
R_in(r)$(ord(r) le 2) = YES;
R_ex('z03')= YES;
*final products*
S_U('s02') = NO;
S_U('s05') = NO;
S_U('s06') = YES;
S_U('s07') = YES;
S_U('s03') = YES;
S_U('s04') = NO;
```

```
*raw materilas*
*S_rm_nonrenew('s01') =  YES;
*S_rm_renew('s08') = YES;
S_rm('s01') = YES;
S_rm('s08') = YES;
*S_rm(s) = S_rm_nonrenew('s01') + S_rm_renew('s08');
*states to be stored*
S_G(s)$(ord(s)) = YES;
S_G('s05') = NO;
S_G('s07') = NO;
S_G('s04') = NO;
S_G('s08') = yes;
S_DISP(r,s)$(NOT S_rm(s)) = YES;
S_DISP('r02','s05') = NO;
S_DISP('r03','s07') = NO;
S_DISP('r02','s04') = YES;
*available states in zones*
*internal
SR('s01','r01')= YES;
SR('s08','r01')= YES;
SR('s02',z)$R_in(r) = YES;
SR('s03','r02')= YES;
SR('s04','r02')= YES;
SR('s05','r02')= YES;
SR('s06','r02')= YES;
SR('s07','r02')= YES;
```

```
*external
SR('s07','r03') = YES;
*storage techno*
Q_G('q-s01') = YES;
Q_G('q-s02_1')= YES;
Q_G('q-s02_2')=YES;
Q_G'q-s03') = YES;
Q_G('q-s06') = YES;
*transfer techno*
Q_TR('q03') = YES;
Q_TR('q04') = YES;
Q_TR('q09') = YES;
*conversion techno*
Q_C('q02') = YES;
Q_C('q05') = YES;
Q_C('q06') = YES;
Q_C('q07') = YES;
Q_C('q08') = YES;
*exploitation techno*
Q_E('q01') = YES;
Q_E('q10') = YES;
*techno that perform task i*
QP('q01','p01') = YES;
QP('q02','p02') = YES;
QP('q03','p03') = YES;
QP('q04','p03') = YES;
```

```
QP('q05','p04') = YES;
QP('q04','p04') = YES;
QP('q05','p05') = YES;
QP('q06','p04') = YES;
QP('q07','p05') = YES;
QP('q08','p05') = YES;
QP('q09','p06') = YES;
*techno installed in zones*
*internal
QR('q01','r01') = YES;
QR('q02','r01') = YES;
QR('q03','r01') = YES;
QR('q03','r02') = YES;
QR('q04','r01') = YES;
QR('q04','r02') = YES;
QR('q05','r02') = YES;
QR('q06','r02') = YES;
QR('q07','r02') = YES;
QR('q08','r02') = YES;
QR('q09','r02') = YES;
*external
QR('q09','r03') = YES;
*storage
QR('q-s01','r01') = YES;
QR('q-s02_1','r01') = YES;
QR('q-s02_2','r02') = YES;
```

```
QR('q-s03','r02') = YES;
QR('q-s06','r02') = YES;
QR('q-s08','r01') = YES;
*tasks that have input raw materials
PS_rm('p01','s01') = YES;
PS_rm('p07','s08') = YES;
*tasks that transfer states*
PS_T('i03','s02') = YES;
PS_T('i06','s07') = YES;
*tasks that have a state as input*\
PS_in('p02','s01') = YES;
PS_in('p04','s02') = YES;
PS_in('p05','s05') = YES;
PS_out('p02','s02') = YES;
PS_out('p04','s05') = YES;
PS_out('p04','s03') = YES;
PS_out('p04','s04') = YES;
PS_out('p05','s06') = YES;
PS_out('p05','s07') = YES;
LOOP(p, QS(q,s)$(QP(q,p) and (PS_in(p,s) or PS_out(p,s) or PS_T(p,s)
or PS_rm(p,s))) = YES; );
QS('q-s01','s01') = YES;
QS('q-s02_1','s02') = YES;
QS('q-s02_2','s02') = YES;
QS('q-s03','s03') = YES;
QS('q-s06','s06') = YES;
```

```
*LOOP(j, ZZ_t(z,zz)$(JZ(j,z) and JZ(j,zz) and J_T(j) and ord(z) ne
ord(zz) and Z_in(zz)) = YES; );

RR_t('r01','r02')= YES;

RR_t('r02','r03')= YES;

DISPLAY TIP_t,R_in,R_ex,
S_U,S_rm,S_G,SR,Q_TR,Q_C,JQ,Q_E,QP,QS,QR,PS_in,PS_out,PS_T,RR_t,IS_rm
;

PARAMETERS

alpha_min(r,rr,p,q,t)   minimum availability percentage of output
                        state s from task i [IS_out(is)] using
                        technology q between zones r rr

alpha_max(r,rr,p,q,t)   maximum availability percentage of output
                        state s from task p [PS_out(ps)] using
                        technology q between zones r and rr

beta_min(r,s,t)   minimum inventory level of state S_G in region r in
                  time period t

beta_max(r,s,t)   maximum inventory level of state S_G in region r in
                  time period t

gamma_min(r,q,t)  minimum capacity of technology q whose installation
                  can start in r in time period t

gamma_max(r,q,t)  maximum capacity of technology q whose installation
                  can start in r in time period t

delta(r,q,t)      fixed operating cost for the total installed
                  capacities of technology q

epsilon(r,q,t)    investment required (per unit) for increasing the
                  capacity of technology q in region r in time period
                  t

epsilon0(r,q,t)   initial investment cost required to establish a
                  technology

zeta(r,q,t) demand for useful product state in region r in time period
            t
```

```
eta(r,s,t)  co-efficient for deterioration of states that can be
stored

kappa_in(s,p,q)    coefficient for input state s of task p [PS_in(ps)]
                   performed from technology q of region r in time
                   period z

kappa_out(s,p,q)  coefficient for output state s of task p PS_out(ps)]
                   performed from tech q of region r in time period z

lambda(r,s,t)      coefficient of holding cost for storable states

mu(r,q,t)   Time for installation for technology q in region r or the
            duration of constructing an additional facility for an
            implementation start in period t

omega(r,s,t)       maximum avalaible amount of state S_rm in region r
                   in time period t

omega_renew(r,s,t)      maximum available amount of renewable state in
                        region r in time period t

omega_nonrenew (r,s,t)  maximum available amount of nonrenewable state
                        in region r in time period t

ppi(r,s,r,q,t)     cost of production of states through conversion
                   technology

psi_r(r,s,p,q,t)  cost for raw materials

psi_rt(rr,r,s,p,q,t)    costs for state s transfer through technology
                        q from region rr to r both in the R_in

psi(rr,r,s,p,q,t) purchase of raw materia state from regions outside
                   of R_in

c0(r,q)     initial installed capacity of technology q in region r (in
t=0)

g0(r,s)     initial available inventory of state s in region r (in
t=0)

ex(rr,r,s,p,q,t)  purchase of useful product state from external
region r

ff0(r,rr,q),cg0(r,s,j),lambda_disp(r,s,t), mu_t(r,rr,q,t);
```

```
ex(r,rr,s,p,q,t)

test_p(r,s,p,q,t)       production

test_d(rr,r,s,p,q,t)          connections on transportation networks

lambda_disp(r,s,t)

mu_t(r,rr,q,t);

alpha_min(r,rr,p,q,t)$(TIP_t(t)) = 0;

alpha_max(r,rr,p,q,t)$(TIP_t(t)) = 1;

beta_min(r,s,t)$(TIP_t(t) AND S_G(s)) = 0.5;

beta_max(r,s,t)$(TIP_t(t) AND S_G(s)) = 1;


gamma_min(r,'q02',t)$(TIP_t(t)) = 5;

gamma_max(r,'q02',t)$(TIP_t(t)) = 50;

gamma_min(r,'q05',t)$(TIP_t(t)) = 10;

gamma_max(r,'q05',t)$(TIP_t(t)) = 40;

gamma_min(r,'q06',t)$(TIP_t(t)) = 10;

gamma_max(r,'q06',t)$(TIP_t(t)) = 40;

*i5 task

gamma_min(r,'q07',t)$(TIP_t(t)) = 5;

gamma_max(r,'q07',t)$(TIP_t(t)) = 30;

gamma_min(r,'q08',t)$(TIP_t(t)) = 5;

gamma_max(r,'q08',t)$(TIP_t(t)) = 30;

*transfer technology

gamma_min(r,'q03',t)$(TIP_t(t)) = 0;

gamma_max(r,'q03',t)$(TIP_t(t)) = 30;

gamma_min(r,'q04',t)$(TIP_t(t)) = 0;

gamma_max(r,'q04',t)$(TIP_t(t)) = 30;
```

```
*i6 task

gamma_min(r,'j09',t)$(TIP_t(t)) = 0;

gamma_max(r,'j09',t)$(TIP_t(t)) = 50;

*storage

gamma_min(r,j,t)$(TIP_t(t) AND J_B(j)) = 10;

gamma_max(r,'q-s01',t)$(TIP_t(t)) = 100;

gamma_max(r,'q-s02_1',t)$(TIP_t(t)) = 100;

gamma_max(r,'q-s02_2',t)$(TIP_t(t)) = 100;

gamma_max(r,'q-s03',t)$(TIP_t(t)) = 100;

gamma_max(r,'q-s06',t)$(TIP_t(t)) = 100;

*conversion tech

delta(r,'q02',t)$(TIP_t(t)) = 15;

delta(r,'q05',t)$(TIP_t(t)) = 20;

delta(r,'q06',t)$(TIP_t(t)) = 40;

delta(r,'q07',t)$(TIP_t(t)) = 30;

delta(r,'q08',t)$(TIP_t(t)) = 25;

*conversion tech

epsilon(r,'q02',t)$(TIP_t(t)) = 2000;

epsilon(r,'q05',t)$(TIP_t(t)) = 3000;

epsilon(r,'q06',t)$(TIP_t(t)) = 3500;

epsilon(r,'q07',t)$(TIP_t(t)) = 3000;

epsilon(r,'q08',t)$(TIP_t(t)) = 2600;

*transfer tech

epsilon(r,'q03',t)$(TIP_t(t)) = 900;

epsilon(r,'q04',t)$(TIP_t(t)) = 800;

epsilon(r,'q09',t)$(TIP_t(t)) = 800;
```

```
storage technology
epsilon(r,'q-s01',t)$(TIP_t(t)) = 50;
epsilon(r,'q-s08',t)$(TIP_t(t)) = 50;
epsilon(r,'q-s02_1',t)$(TIP_t(t)) = 50;
epsilon(r,'q-s02_2',t)$(TIP_t(t)) = 50;
epsilon(r,'q-s03',t)$(TIP_t(t)) = 50;
epsilon(r,'q-s06',t)$(TIP_t(t)) = 50;
*conversion tech
epsilon0(r,'q02',t)$(TIP_t(t)) = 20000;
epsilon0(r,'q05',t)$(TIP_t(t)) = 30000;
epsilon0(r,'q06',t)$(TIP_t(t)) = 25000;
epsilon0(r,'q07',t)$(TIP_t(t)) = 20000;
epsilon0(r,'q08',t)$(TIP_t(t)) = 26000;
*transfer tech
epsilon0(r,'q03',t)$(TIP_t(t)) = 9000;
epsilon0(r,'q04',t)$(TIP_t(t)) = 8000;
epsilon0(r,'q09',t)$(TIP_t(t)) = 8000;
*storage
epsilon0(r,'q-s01',t)$(TIP_t(t)) = 1000;
epsilon0(r,'q-s02_1',t)$(TIP_t(t)) = 1000;
epsilon0(r,'q-s02_2',t)$(TIP_t(t)) = 1000;
epsilon0(r,'q-s03',t)$(TIP_t(t)) = 1000;
epsilon0(r,'q-s06',t)$(TIP_t(t)) = 1000;
zeta(r,s,'t01')$Z_in(z) = 0;
kappa_in('s01','p02','q02') = 1;
kappa_in('s02','p03','q03') = 1;
```

```
kappa_in('s02','p03','q04') = 1;

kappa_in('s02','p04','q05') = 1;

kappa_in('s02','p04','q06') = 1;

kappa_in('s05','p05','q07') = 1;

kappa_in('s05','p05','q08') = 1;

kappa_in('s07','p06','q09') = 1;

kappa_out('s02','p02','q02') = 1;

kappa_out('s02','p03','q03') = 1;

kappa_out('s02','p03','q04') = 1;

kappa_out('s03','p04','q05') = 1;

kappa_out('s03','p04','q06') = 1;

kappa_out('s05','p04','q05') = 1;

kappa_out('s05','p04','q06') = 1;

kappa_out('s06','p05','q07') = 1;

kappa_out('s06','p05','q08') = 1;

kappa_out('s07','p05','q07') = 1;

kappa_out('s07','p05','q08') = 1;

kappa_out('s07','p06','q09') = 1;

kappa_out('s04','p04','q05') = 5;

kappa_out('s04','p04','q06') = 10;

eta(r,'s05',t)$(R_in(r)and TIP_t(t))= 0.15;

eta(r,'s06',t)$(R_in(r)and TIP_t(t))= 0;

lambda(r,s,t)$(S_G(s) and R_in(r)and TIP_t(t)) = 0.2;

mu('r01','q02',t)$(TIP_t(t))= 1;

mu('r02','q05',t)$(TIP_t(t))= 1;

mu('r02','q06',t)$(TIP_t(t))= 1;
```

```
mu('r02','q07',t)$(TIP_t(t))= 1;

mu('r02','q08',t)$(TIP_t(t))= 1;

mu_t(r,rr,q,t) = 1;

omega(r,s,t)$(S_rm(s) and SR(s,r) and R_in(r)and TIP_t(t)) = 5-00;

ppi(r,s,'p02','q02',t)$(TIP_t(t))  = 12;

ppi(r,s,'p04','q05',t)$(TIP_t(t))  = 20;

ppi(r,s,'p04','q06',t)$(TIP_t(t)) = 25;

ppi(r,s,'p05','q07',t)$(TIP_t(t)) = 30;

ppi(p,s,'p05','q08',t)$(TIP_t(t)) = 40;

*exploitation  - RC1

psi_r(r,s,p,q,t)$(R_in(r) and S_rm(s) and SR(s,r) and QS(q,s) and
QP(q,p) and QZ(q,r) and Q_E(q) and PS_rm(p,s)and TIP_t(t)) = 50;

*transfer  - RC2

psi_rt(rr,r,s,p,q,t)$(R_in(r) and R_in(rr) and S_rm(s) and SR(s,r) and
SR(s,rr) and QS(q,s) and QP(q,p) and ord(r) ne ord(rr)and QR(q,r) and
Q_TR(q) and PS_T(p,s) and RR_t(rr,r)and TIP_t(t)) = 0.25;

*purchase rm from external- RC3

psi(rr,r,s,p,q,t)$(not R_in(rr) and R_in(r) and S_rm(s) and SR(s,r)
and SR(s,rr) and QR(q,r) and QR(q,r) and QS(q,s) and QP(q,p)and
Q_TR(q) andRRS_T(i,s) and RR_t(rr,r)and TIP_t(t)) = 1;

c0(r,q)$R_in(r) = 0;

g0(r,s)$(R_in(r) and SR(s,r)) = 0;

cc0(r,rr,q)=0;

ex(rr,r,s,p,q,t)$(R_in(r) and not R_in(rr) and RR_t(rr,r) and S_U(s)
and SR(s,r) and SR(s,rr)and QR(q,r) and QR(q,rr) and QS(q,s) and
QP(q,Q) and Q_TR(q) and PS_T(p,s)and TIP_t(t)) =1000000;

ex(rr,r,s,p,q,t)$(R_in(r) and R_in(rr) and RR_t(rr,r) and S_U(s) and
SR(s,r) and SR(s,rr)and QR(q,r) and QR(q,rr) and QS(q,s) and QP(q,p)
and Q_TR(q) and PS_T(p,s)and TIP_t(t)) = 50;
```

```
ex(rr,r,s,p,q,t)$(Rex(r) and R_in(rr) and RR_t(rr,r) and S_U(s) and
SR(s,r) and SR(s,rr)and QR(q,r) and QR(q,rr) and QS(q,s) and QP(q,p)
and Q_TR(q) and PS_T(p,s)and TIP_t(t)) = 20;

test_p(r,s,p,q,t)$(R_in(r) and SR(s,r) and PS_out(p,s) and QP(q,p) and
QR(q,r) and Q_C(q)and TIP_t(t))=1;

test_d(rr,r,s,p,q,t)$(S_U(s) and R_in(rr) and SR(s,r) and SR(s,rr) and
QP(q,p) and PS_T(p,s) and QR(q,r) and QR(q,rr) and Q_TR(q) and
RR_t(rr,r)and TIP_t(t))=1;

S_UNDESIRED('s04') = YES;

lambda_disp(r,s,t) = 0;

DISPLAY
p,q,s,t,alpha_max,gamma_min,gamma_max,beta_min,beta_max,kappa_in,kappa
_out,g0,delta,eta,lambda,mu,ppi,psi_z,psi_zt,psi,omega,c0,cc0,ex,
test_p,test_d,S_DISP;
```

B.4 GAMS illustration for coal-only fired plants

```
OLUWATOSIN MURELE

* A General Representation for Modeling Operations in Energy Supply
Chains

OPTION   MIP = CPLEX, RESLIM = 1000000000, ITERLIM = 1000000000;

OPTION   OPTCR = 0.00, LIMROW = 1e8, LIMCOL=1e8;

SETS

p      tasks(conversion &transfer)

q      technologies (conversion & transfer & storage)

s      states (energy material resources & energy forms & pollutants)

t      time periods

r      regions ;

ALIAS (r,rr),(t,tt) ;

SETS

R_in(r)      regions r that are part of the local (internal) energy
network

S_U(s)       states that have demand in region r (represented as demand
             or useful products states)

S_rm(s)      states s that are considered as raw materials

S_G(s)       states s that can be stored

S_G_lim(s)   capacity of storage states s

Q_C(q)       conversion technologies q

Q_TR(q)      transfer technologies q

Q_G(q)       storage technologies q

Q_E(q)       local exploitation technology q (imaginary tranfer of
             locally available state with the same region r)

PS_in(p,s)   input states s to task p
```

```
PS_out(p,s) output states s to task p

PS_rm(p,s)  input local available states s (raw materials) to task p

PS_T(p,s)   tranfer task p for state s

QP(q,p)     technologies q that can perform task p

QS(q,s)     technologies q that involve state s

QR(q,r)     technologies q that can be installed in region r

SR(s,r)     states s for which a task can take place in region r

RR_t(r,rr)  available state flows from region r to regions rr

TIP_t(t)    time periods

S_UNDESIRED(s)    undesired state

S_DISP(r,s)       disposed state

S_rm_nonrenew(s)  Nonrenewable raw material state;
```

PARAMETERS

```
alpha_min(r,rr,p,q,t)   minimum availability percentage of output
                        state s from task p [PS_out(ps)] using
                        technology q between regions r rr

alpha_max(r,rr,p,q,t)   maximum availability percentage of output
                        state s from task p [PS_out(ps)] using
                        technology q between regions r and rr

beta_min(r,s,t)   minimum inventory level of state S_G in region r in
                  time period t

beta_max(r,s,t)   maximum inventory level of state S_G in region r in
                  time period t

gamma_min(r,q,t)  minimum capacity of technology q whose installation
                  can start in r in time period t

gamma_max(r,q,t)  maximum capacity of technology q whose installation
                  can start in r in time period t
```

delta(r,q,t)	fixed operating cost for the total installed capacities of technology q
epsilon(r,q,t)	investment required (per unit) for increasing the capacity of technology q in region r in time period t
epsilon0(r,q,t)	initial investment cost required to establish a technology
zeta(r,q,t)	demand for useful product state in region r in time period t
eta(r,s,t)	co-efficient for deterioration of states that can be stored
kappa_in(s,p,q)	coefficient for input state s of task p [PS_in(ps)] performed from technology q of region r in time period t
kappa_out(s,p,q)	coefficient for output state s of task p [PS_out(ps)] performed from tech q of region r in time period t
lambda(r,s,t)	coefficient of holding cost for storable states
mu(r,q,t)	Time for installation for technology q in region r or the duration of constructing an additional facility for an implementation start in period t
omega(r,s,t)	maximum avalaible amount of state S_rm in region r in time period t
omega_nonrenew (r,s,t)	aximum available amount of nonrenewable state in region r in time period t
ppi(r,s,r,q,t)	cost of states production through conversion technology
psi_r(r,s,p,q,t)	raw materials cost
psi_rt(rr,r,s,p,q,t)	transferring cost for state s through technology q from region rr to r both in the R_in

```
psi(rr,r,s,p,q,t) purchase of raw materia state from regions outside
                  of R_in

c0(r,q)     initial installed capacity of technology q in region r (in
t=0)

g0(r,s)     initial available inventory of state s in region r (in
t=0)

ex(rr,r,s,p,q,t)  purchase of final product state from external region
r

ff0(r,rr,q),cg0(r,s,j),lambda_disp(r,s,t), mu_t(r,rr,q,t);

$include ICCE_TEST3

BINARY VARIABLES

V(r,q,t)    equals to 1 if biomass exploitation, pre-processing and
conversion technologies q are established for the first time in region
r at time period t, zero if otherwise.

VG (r,s,q,t)      equals to 1 if storage technology q for state s is
established for the first time in region r at time period t, zero if
otherwise.

Z(r,q,t)    equals to 1 if capacity of biomass exploitation, pre-
processing and conversion technology q begins installing in region r
in time period t, zero if otherwise.

Z_TR(r,rr,j,t)    equals to 1 if capacity of transfer technology q
starts installing in region r in time period t, zero if otherwise.

ZG(r,s,q,t)        equals to 1 if capacity of storage technology q
begins installing in region rin time period t, zero if otherwise.


POSITIVE VARIABLES

M(r,rr,p,q,t)     stock quantity of state s converted or transferred
through task p using q from r to rrin time period t

G(r,s,t)    stock of state that remain in region r at the end of time
period t
```

C(r,q,t)	overall capacity of conversion technology q that can store states in region r at time interval t
C_TR(r,rr,j,t)	overall capacity of transfer technology q that can transfer state from one region to another
E(r,q,t)	capacity increase of conversion technology q in region r in time period t
E_TR(r,rr,q,t)	capacity increase of transfer technology that can transfer state from one region to another in time period t
CG(r,s,q,t)	overall capacity of storage technology q that can store state in region r, at time interval t
EG(r,s,q,t)	I capacity increase of storage technology
DISPOSED(r,s,t)	disposed state
D	Quantity of disposed state
FAC(t)	fixed assets cost in time period t
FOC(t)	fixed operating cost in time period t
VOC(t)	variable operating cost in time period t
IC(t)	cost of inventory for states in time period t
HC(t)	cost of producing useful products states in time period t
CM(t)	cost of raw materials at every time period t
CM1(t)	cost of exploitation of local raw material states available in each region r
CM2(t)	raw material states transportation cost within R_in
CM3(t)	purchase cost for raw materials from regions outside R_in
TRC(t)	transfer cost for final product states within internal zones and external sales of final product states to external zones
C_TR(t)	overall capacity of transfer technology q
DC(t)	cost of disposing unwanted states to the environment (penalty)

```
N(r,s,t)     quantity of states with unmet demand

NS(t)        penalty (cost) for no-sales, ie unmet demands ;

VARIABLE

OF    objective function (total cost);

EQUATIONS        EQ1,EQ2a,EQ2b, EQB1,EQB2a,EQB2b, EQt1,EQ2ta,EQ2tb,
EQ3pa,EQ3pb,EQ3ta,EQ3tb,EQ4a,EQ4b,EQ6,EQ7,
EQ8,EQ8B,EQ9,EQ9B,EQ10,EQ10B,EQ11,EQ11t,EQ11B,EQ12,
EQ13,EQ14,EQ15,EQ15b, EQ16,EQ17,EQ18,EQ19,EQ20, EQ21;
```

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*==================== D E S I G N
========================================

EQ1(r,q,t) $(TIP_t(t) AND R_in(r) and QR(q,r) and not (Q_TR(q) or
Q_G(q)))..      C(r,q,t) =e= C(r,q,t-1)$(ord(t)>1) + c0(r,q)$(ord(t)=1)
+ E(r,q,t);

EQ2a(r,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and not (Q_TR(q) or
Q_G(q)))..      E(r,q,t) =g= gamma_min(r,q,t)*R(r,q,t-mu(r,q,t));

EQ2b(r,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and not (Q_TR(q) or
Q_G(q))).. E(r,q,t) =l= gamma_max(r,q,t)*Z(r,q,t-mu(r,q,t));

EQB1(r,s,q,t) $(TIP_t(t) AND R_in(r) and QR(q,r) and SR(s,r) and
Q_G(q) AND QS(q,s) AND S_G_lim(s)).. CG(r,s,q,t) =e= CG(r,s,q,t-
1)$(ord(t)>1) + cg0(r,s,q)$(ord(t)=1) + EG(r,s,q,t);

EQB2a(r,s,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and SR(s,r) and
Q_G(q) AND QS(q,s) AND S_G_lim(s)).. E_G(r,s,q,t) =g=
gamma_min(r,q,t)*ZG(r,s,q,t-mu(r,q,t));

EQB2b(r,s,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and SR(s,r) and Q_G(q)
AND     QS(q,s)AND      S_G_lim(s))..      EG(r,s,q,t)      =l=
gamma_max(r,q,t)*ZG(r,s,q,t-mu(r,q,t));

EQt1(r,rr,q,t) $(TIP_t(t) AND R_in(r) and QR(q,r) and QR(q,rr) and
Q_TR(q) and RR_t(r,rr)).. C_TR(r,rr,q,t) =e= C_TR(r,rr,q,t-1)$(ord(t)>1)
+ cc0(z,zz,j)$(ord(t)=1) + E_TR(r,rr,q,t);

EQ2ta(r,rr,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and QR(q,rr) and
Q_TR(q)     and     RR_t(r,rr))..         E_TR(r,rr,q,t)      =g=
gamma_min(r,q,t)*Z_TR(r,rr,q,t-mu_t(r,rr,q,t));

EQ2tb(r,rr,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and QR(q,rr) and
Q_TR(q)       and       RR_t(r,rr))..      E_TR(r,rr,q,t)       =l=
gamma_max(r,q,t)*Z_TR(r,rr,q,t-mu_t(r,rr,q,t));
```

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*========= L I N K  D E S I G N - P L A N N I N G
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EQ3pa(r,p,q,t)$(TIP_t(t) AND (Q_C(q) OR Q_E(q)) and R_in(r) and QP(q,p)
and QR(q,r)).. M(r,r,p,q,t) =g= alpha_min(r,r,p,q,t)*C(r,q,t);

EQ3pb(r,p,q,t)$(TIP_t(t) AND (Q_C(q) OR Q_E(q)) and R_in(r) and QP(q,q)
and QR(q,r)).. M(r,r,p,q,t) =l= alpha_max(r,r,p,q,t)*C(r,q,t);

EQ3ta(r,rr,p,q,t)$(TIP_t(t) AND Q_TR(q) and QP(q,p) and QR(q,r) and
QR(q,rr) and RR_t(r,rr)).. M(r,rr,p,q,t) =g=
alpha_min(r,rr,p,q,t)*C_TR(r,rr,q,t);

EQ3tb(r,rr,p,q,t)$(TIP_t(t) AND Q_TR(q) and QP(q,p) and QR(q,r) and
QR(q,rr) and RR_t(r,rr)).. M(r,rr,p,q,t) =l=
alpha_max(r,rr,p,q,t)*C_TR(r,rr,q,t);

EQ4a(r,s,t)$(TIP_t(t) AND S_G_lim(s) and R_in(r) and SR(s,r)).. G(r,s,t)
=g= beta_min(r,s,t)*SUM(q$(QR(q,r) and Q_G(q) and QS(q,s)),
CG(r,s,q,t));

EQ4b(r,s,t)$(TIP_t(t) AND S_G_lim(s) and R_in(r) and SR(s,r)).. G(r,s,t)
=l= beta_max(r,s,t)*SUM(q$(QR(q,r) and Q_G(q) and QS(q,s)),
CG(r,s,q,t));


*================= P L A N N I N G
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EQ5(r,s)$(S_rm(s) AND S_rm_nonrenew(s) and SR(s,r))..
SUM((p,q,t)$(TIP_t(t) AND Q_E(q) and R_in(r) and PS_rm(p,s) and
QP(q,p) and QR(q,r)),M(r,r,p,q,t)) =l=
SUM(t$(ORD(t)=1),omega(r,s,t));…

EQ6(r,s)$(S_rm(s) AND S_rm_nonrenew(s) and SR(s,r))..
SUM((p,q,t)$(TIP_t(t) AND Q_E(q) and R_in(r) and PS_rm(p,s) and
QP(q,p) and QR(q,r)),M(r,r,i,j,t)) =l= SUM(t$(ORD(t)=1),omega(r,s,t));

EQ7(r,s,t)$(TIP_t(t) and SR(s,r)).. G(r,s,t)$S_G(s) =e=
g0(r,s)$(S_B(s) and ord(t)=1) + (1-eta(r,s,t))*G(r,s,t-1)$(S_G(s) AND
ord(t)>1) + SUM((rr,p,q)$(Q_TR(q) and PS_T(p,s) and QR(q,r) and
QR(q,rr) and QP(q,p) and rr_t(rr,r)), kappa_out(s,p,q)*M(rr,r,p,q,t))-
SUM((rr,p,q)$(Q_TR(q) and PS_T(p,s) and QR(q,r) and QR(q,rr) and
QP(q,p) and RR_t(r,rr)),  kappa_in(s,p,q)*M(r,rr,p,q,t))+
```

```
SUM((p,q)$(Q_C(q) and PS_out(p,s) and QR(q,r) and QP(q,p)),
kappa_out(s,p,q)*M(r,r,p,q,t))
```

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================== E C O N O M I C
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EQ8(r,q)$(R_in(r) and QR(q,r) and not (Q_TR(q) or Q_G(q)))..
SUM(t$(TIP_t(t)), V(r,q,t)) =l= 1;

EQ9(r,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and not (Q_TR(q) or
Q_B(q))).. V(r,q,t) =l= Z(r,q,t);

EQ10(r,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and not (Q_TR(q) or
Q_G(q))).. V(r,q,t) =g= Z(r,q,t) - SUM(tt$(ord(tt) < ord(t)),
V(r,q,tt));

EQ8B(r,s,q)$(R_in(r) and QR(q,r) and QS(q,s) and Q_G(q))..
SUM(t$(TIP_t(t)), VG(r,s,q,t)) =l= 1;

EQ9B(r,s,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and QS(q,s) and
Q_G(q)).. VG(r,s,q,t) =l= ZG(r,s,q,t);

EQ10B(r,s,q,t)$(TIP_t(t) AND R_in(r) and QR(q,r) and QS(q,s) and
Q_G(q)).. VG(r,s,q,t) =g= ZG(r,s,q,t) - SUM(tt$(ord(tt) < ord(t)),
VG(r,s,q,tt));

EQ11(t)$TIP_t(t).. FAC(t) =e= SUM((r,q)$(R_in(r) and QR(q,r) and not
(Q_TR(q) or Q_G(q))), epsilon0(r,q,t)*V(r,q,t) +
epsilon(r,q,t)*E(r,q,t))+ SUM((r,s,j)$(R_in(r) and QR(q,r) and QS(q,s)
and not (Q_TR(q) or Q_E(q) or Q_C(q))),epsilon0(r,q,t)*VG(r,s,q,t) +
epsilon(r,q,t)*EG(r,s,q,t));

* investment for transfer network

EQ11t(t)$TIP_t(t).. C_TR(t) =e= SUM((r,rr,q)$(TIP_t(t) AND R_in(r) AND
QR(q,r) and QR(q,rr) and Q_TR(q) and RR_t(r,rr)),
epsilon(r,q,t)*E_TR(r,rr,q,t) + epsilon0(r,q,t)*ZT(r,rr,q,t));

EQ11B(t)$TIP_t(t).. GT(t) =E= SUM((r,s,q)$(R_in(r) and QR(q,r) and
SR(s,r) and Q_G(j) AND QS(q,s)), epsilon(r,q,t)*EG(r,s,q,t));

EQ12(t)$TIP_t(t).. FOC(t) =e= SUM((r,q)$(R_in(r) and QR(q,r) and not
(Q_TR(q) or Q_G(q))), delta(r,q,t)*C(r,q,t));

EQ13(t)$TIP_t(t).. VOC(t) =e= CM(t) + HC(t) + IC(t) - TRC(t) + DC(t);
```

```
*EQ14(t)$TIP_t(t).. HC(t) =e= SUM((r,s,p,q)$(R_in(r) and Q_C(q) and
SR(s,r) and PS_out(p,s) and QR(q,r) and QP(q,p)),
ppi(r,s,p,q,t)*M(r,r,p,q,t));

EQ15(t)$TIP_t(t).. IC(t) =e= SUM((r,s)$(R_in(r) and S_G(s) and
SR(s,r)), lambda(r,s,t)*G(r,s,t));



EQ15b(t)$TIP_t(t).. DC(t) =e= SUM((r,s)$(R_in(r) and S_DISP(r,s) and
SR(s,r)), lambda_disp(r,s,t)*DISPOSED(r,s,t));

*EQ16(t)$TIP_t(t).. CM1(t) =e= SUM((r,s,p,q)$(R_in(r) and S_rm(s) and
SR(s,r) and QS(q,s) and QP(q,p) and QR(q,r) and Q_E(q) and
PS_rm(p,s)),

 psi_r(r,s,p,q,t)*M(r,r,p,q,t));

EQ17(t)$TIP_t(t).. CM2(t) =e= SUM((r,rr,s,p,q)$(R_in(r) and R_in(rr)
and S_rm(s) and SR(s,r) and SR(s,rr) and QS(q,s) and QP(q,p) and
ord(rr) ne ord(r)and QR(q,r) and QR(q,rr) and Q_TR(q) and PS_T(p,s)
and RR_t(r,rr)), psi_rt(r,rr,s,p,q,t)*M(r,rr,p,q,t));

EQ18(t)$TIP_t(t).. CM3(t) =e= SUM((rr,r,s,p,q)$(not R_in(rr) and
R_in(r) and S_rm(s) and SR(s,r) and SR(s,rr) and QR(q,r) and QR(q,rr)
and QS(q,s) and QP(q,p)and Q_TR(q) and PS_T(p,s) and RR_t(rr,r)),
psi(rr,s,p,q,t)*M(rr,r,p,q,t));

EQ19(t)$TIP_t(t).. CM(t) =e= CM1(t) + CM2(t) + CM3(t);

EQ20(t)$TIP_t(t).. TRC(t) =e= SUM((rr,r,s,p,q)$(R_in(rr) and
RR_t(rr,z) and S_U(s) and SR(s,r) and SR(s,rr)and QR(q,r) and QR(q,rr)
and QS(q,s) and QP(q,p) and Q_TR(q) and PS_T(p,s)),
ex(rr,r,s,p,q,t)*M(rr,r,p,q ,t));

EQ21..OF =e= SUM (t$TIP_t(t), FAC(t) + TRC(t) + FOC(t) + VOC(t))+ SUM
((r,s,t)$(TIP_t(t) AND zeta(r,s,t)>0), 100000*INFEASIBLE(r,s,t));

MODEL        STN_MODEL /ALL/;

*zeta(r,s,'t01')$R_in(r) = 0;

zeta('r02','s03',t)$(ORD(t) GE 3 AND ORD(t) LE 5) =
round(uniform(35,45));
```

```
zeta('r02','s03',t)$(ORD(t) GE 6 AND ORD(t) LE 10) =
round(uniform(50,60));

zeta('r02','s03',t)$(ORD(t) GE 11 AND ORD(t) LE 20) =
round(uniform(60,70));

zeta('r02','s06',t)$(ORD(t) GE 3 AND ORD(t) LE 5) =
round(uniform(20,40));

zeta('r02','s06',t)$(ORD(t) GE 6 AND ORD (t) LE 10) =
round(uniform(50,70));

zeta('r02','s06',t)$(ORD(t) GE 11 AND ORD (t) LE 20) =
round(uniform(90,110));

zeta('r02','s07',t)$(ORD(t) GE 2 AND ORD(t) LE 5) =
round(uniform(10,35));

zeta('r02','s07',t)$(ORD(t) GE 6 AND ORD(t) LE 10) =
round(uniform(30,60));

zeta('r02','s07',t)$(ORD(t) GE 11 AND ORD(t) LE 20) =
round(uniform(60,120));

zeta('r03','s07',t)$(ORD(t) GE 2 AND ORD(t) LE 5) =
round(uniform(10,30));

zeta('r03','s07',t)$(ORD(t) GE 6 AND ORD(t) LE 10) =
round(uniform(20,40));

zeta('r03','s07',t)$(ORD(t) GE 11 AND ORD(t) LE 20) =
round(uniform(50,70));

zeta('r03','s07',t)$(ORD(t) GE 21 AND ORD(t) LE CARD(t)) =
round(uniform(60,100));

g0(r,'s01')= 10000;

zeta('r02','s03',t)$(ORD(t) GE 16 AND ORD(t) LE CARD(t)) =
round(uniform(60,90));

zeta('r02','s06',t)$(ORD(t) GE 16 AND ORD (t) LE CARD(t)) =
round(uniform(60,90));

zeta('r02','s07',t)$(ORD(t) GE 16 AND ORD(t) LE CARD(t)) =
round(uniform(40,130));
```

```
S_G_lim(s)$(S_G(s) AND NOT S_UNDESIRED(s) AND NOT S_rm(s)) = YES;

cg0(z,s,j)=0;

c0(r,q)=0;

lambda_disp('r02','s04','t01') = 18;

LOOP(t, lambda_disp('r02','s04',t+1) =
0.05*lambda_disp('r02','s04',t)+lambda_disp('r02','s04',t); );

lambda_disp(r,s,'t01')$(NOT S_UNDESIRED(s)) = 500;

LOOP(t, lambda_disp(r,s,t+1)$(NOT S_UNDESIRED(s)) =
1.1*lambda_disp(r,s,t););

lambda(r,s,'t01')$(S_G(s) and R_in(r)) = 0.1;

LOOP(t,lambda(r,s,t+1) = 1.05*lambda(r,s,t); );

epsilon0(r,'q02','t01') = 20000;

LOOP(t, epsilon0(r,'q02',t+1) = 1.2*epsilon0(r,'q02',t); );

epsilon0(r,'q03','t01') = 2000;

LOOP(t, epsilon0('r01','q03',t+1) = 1.01*epsilon0('r01','q03',t); );

epsilon0(r,'q04','t01') = 2000;

LOOP(t, epsilon0('r01','q04',t+1) = 1.01*epsilon0('r01','q04',t); );

epsilon0(r,'q05','t01') = 28000;

LOOP(t, epsilon0(r,'q05',t+1) = 1.1*epsilon0(r,'q05',t); );

epsilon0(r,q,'t01')$Q_G(q) = 1000;

LOOP(t, epsilon0(r,q,t+1)$Q_G(q) = 1.005*epsilon0(r,q,t); );

epsilon(r,'q03',t)$(ORD(t) LE 16) = uniform(1000,1200);

epsilon(r,'q03',t)$(ORD(t) GE 17) = uniform(1200,1300);

epsilon(r,'q04',t)$(ORD(t) LE 16) = uniform(1000,1200);

epsilon(r,'q04',t)$(ORD(t) GE 17) = uniform(1200,1300);

epsilon(r,'q02',t)$(ORD(t) LE 14) = uniform(1300,1800);

epsilon(r,'q02',t)$(ORD(t) GE 15) = uniform(1700,2000);
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```
epsilon(r,'q05',t)$(ORD(t) LE 15) = uniform(3800,4000);

epsilon(r,'q05',t)$(ORD(t) GE 16) = uniform(4100,4200);

epsilon(r,q,t)$(Q_G(q) AND ORD(t) LE 10) = uniform(40,50);

epsilon(r,q,t)$(Q_G(q) AND ORD(t) GE 11) = uniform(60,70);

epsilon(r,q,t)$(ORD(r)=1 AND TIP_t(t) AND R_in(r) AND QR(q,r) and
Q_T(j)) = 0.5*epsilon(r,q,t);

epsilon0(r,q,t)$(ORD(r)=1 AND TIP_t(t) AND R_in(r) AND QR(q,r) and
Q_T(q)) = 0.5*epsilon0(r,q,t);

epsilon(r,q,t)$(Q_E(q) AND QR(q,r) AND TIP_t(t)) =
1100*(1+0.02*ORD(t));

epsilon0(r,q,t)$(Q_E(q) AND QR(q,r) AND TIP_t(t))=
1300*(1+0.02*ORD(t)); ;

mu(r,q,t)$(Q_E(q) AND QR(q,r) AND TIP_t(t)) = 1;

gamma_min(r,q,t)$(Q_E(q) AND QR(q,r) AND TIP_t(t)) = 5;

gamma_max(r,q,t)$(Q_E(q) AND QR(q,r) AND TIP_t(t)) = 50;

S_rm_nonrenew(s)$S_rm(s) = YES;

omega(r,s,t)$(S_rm_nonrenew(s)) = 0;

omega(r,s,t)$(S_rm_nonrenew(s) AND ORD(t)=1) = 2000;

omega('r01','s01',t)$(S_rm_nonrenew('s01') AND ORD(t)=1) = 2000;

g0(r,s)$S_rm_nonrenew(s) = 0;

g0('r01','s01') = 0;

ex('r01','r02','s02','p03','q03',t) = 50;

ex('r01','r02','s02','p03','q04',t) = 50;

ex('r02','r03','s07','p06','q09',t) = 20;

SOLVE       STN_MODEL  using MIP minimizing OF;

DISPLAY  ex,S_DISP,zeta,lambda_disp,g0, OF.l, DISPOSED.l,INFEASIBLE.l,
FAC.l,CT.l,FOC.l, VOC.l,HC.l,IC.l,CM.l,TRC.l,DC.l, CM1.l,CM2.l,CM.l,
M.l,G.l, C.l,E.l,CG.l, C_TR.l,ET.l,EG.l,ZT.l,Z.l,ZG.l,V.l,VG.l;
```

```
PARAMETER COST_FAC1,COST_FAC2;

COST_FAC1(q,t) = SUM((r)$(R_in(r) and QR(q,r) and not (Q_T(q) or
Q_E(q) or Q_G(q))), epsilon0(r,q,t)*V.L(r,q,t) +
epsilon(r,q,t)*E.L(r,q,t));

COST_FAC2(q,t) = SUM((r,s)$(R_in(r) and QR(q,r) and QS(q,s) and not
(Q_T(q) or Q_E(q) or Q_C(q))),epsilon0(r,q,t)*VG.L(r,s,q,t) +
epsilon(r,q,t)*EB.L(r,s,q,t));

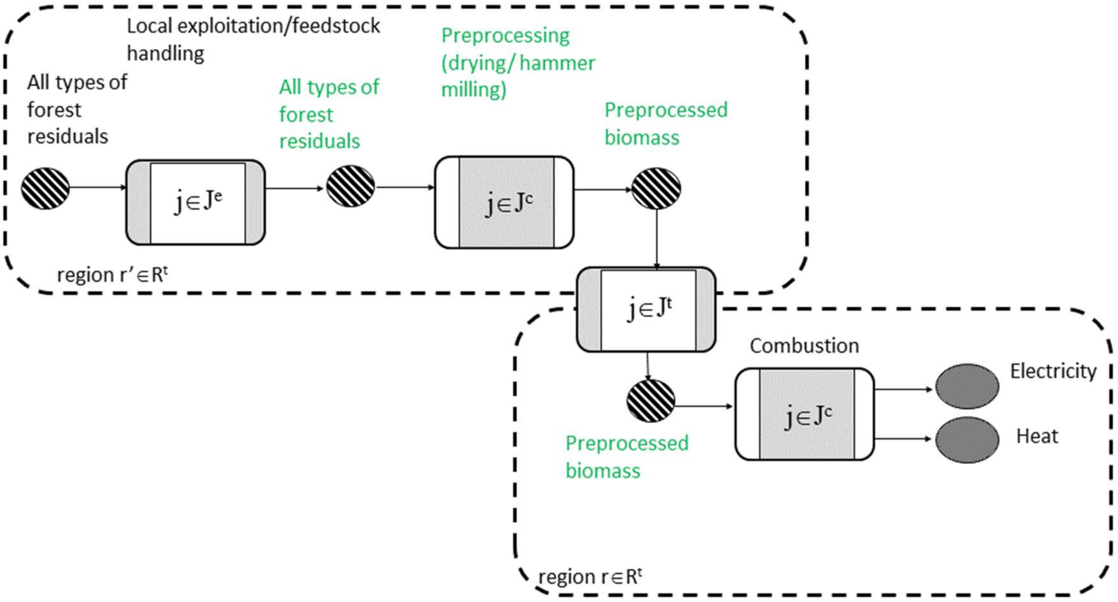
DISPLAY COST_FAC1,COST_FAC2;

PARAMETER Decreased_Omega(r,s,t);

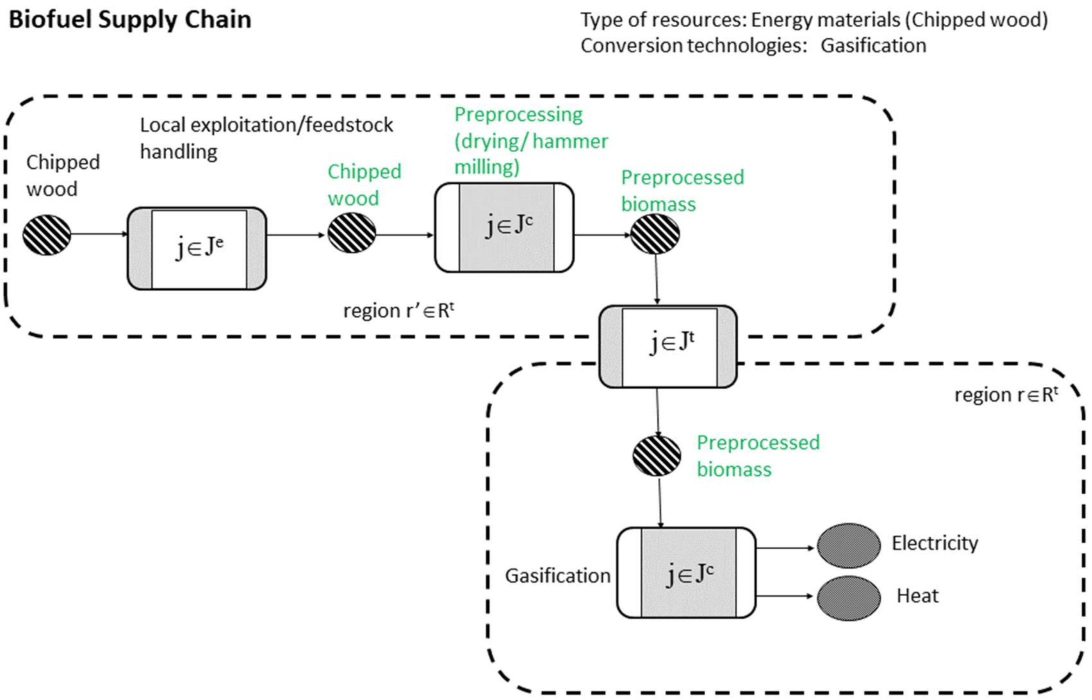
Decreased_Omega(r,s,t)$(S_rm_nonrenew(s) AND SR(s,r) AND ORD(t)>1) =
omega(r,s,'t01') - SUM((p,q,tt)$(TIP_t(t) AND Q_E(q) and R_in(r) and
PS_rm(p,s) and QP(q,p) and QR(q,r) AND ORD(tt) LE
ORD(t)),M.l(r,r,p,q,tt));

DISPLAY Decreased_Omega;
```

B.5 STN representation for biofuel supply chain



B.6 Illustration of gasification in biofuel supply chain using the STN approach



Appendix C **Energy survey using qualtrics online survey tool**

C.1 Cures ethics approval for conducting surveys

From: donotreply@infonetica.net <donotreply@infonetica.net>

Sent: 15 January 2019 11:42

To: Murele, Oluwatosin <Oluwatosin-christiana.Murele@cranfield.ac.uk>

Subject: CURES Submission: Approved

Dear Oluwatosin christiana

Reference: CURES/7618/2019

Title: Design and Planning of Energy supply Chain Networks

Thank you for your application to the Cranfield University Research Ethics System (CURES).

Your proposed research activity has been confirmed as Level 2b risk in terms of research ethics. You may now proceed with the research activities you have sought approval for.

Please remember that CURES occasionally conducts audits of projects. We may therefore contact you during or following execution of your fieldwork. Guidance on good practice is available on the research ethics intranet pages.

If you have any queries, please contact cures-support@cranfield.ac.uk

We wish you every success with your project.

Regards

CURES Team

C.2 Energy survey research questionnaire

Welcome and thanks for taking the time to complete this survey.

Kindly note that, the survey is on general energy types, its generation and usage levels, which should not take more than 20 minutes to complete.

As a result of this, the energy types have been broadly categorized into two: Renewable and non-renewable (conventional).

Respondent's age?
○ 16-25 years
○ 25-40 years
○ 40-65 years
○ Above 65 years

What is your gender?
○ Male
○ Female
○ Do not wish to specify

Respondent's stake in energy usage?
○ Student
○ Lecturer
○ Operator
○ Manager
○ Government
○ Others

Respondent's highest degree/qualification?
○ PhD
○ Master
○ First degree
○ GCSE
○ Other

https://cranfielduniversity.eu.qualtrics.com/jfe/previewForm/SV_1B5mtINrbasRcTr?

Energy research survey

What type of energy do you use?

- ○ Renewable
- ○ Non-renewable
- ○ Combination of non-renewable and renewable

Which area of renewable energy do you explore or plan to explore?

- ○ Biomass
- ○ Geothermal Power
- ○ Marine Power
- ○ Solar power
- ○ Wind Power
- ○ Not Applicable

Are you/your company involved in renewable energy generation?

- ○ Definitely yes
- ○ Probably yes
- ○ Might or might not
- ○ Probably not
- ○ Definitely not

Are you/your company involved in renewable energy usage?

- ○ Definitely yes
- ○ Probably yes
- ○ Might or might not
- ○ Probably not
- ○ Definitely not

What are the reasons for exploration of renewable energy?

- ○ Cost reduction
- ○ Revenue generation
- ○ Greener environment

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15/01/2019

Energy research survey

What level will you classify your primary renewable energy activity?

- ○ Micro generation
- ○ Macro generation
- ○ Transmission
- ○ Distribution
- ○ User
- ○ Not applicable

How often do you use renewable energy in addition to conventional sources of energy (fossil fuel)?

- ○ Less than 4 days per week
- ○ 4 or more days per week
- ○ 2-3 times per month
- ○ Once every 2-3 months
- ○ Once every 6 Months
- ○ Once per year
- ○ Never

How much do you pay for energy usage on a monthly basis?

- ○ £0-£50
- ○ £51-£1100
- ○ £101-£200
- ○ £201-£500
- ○ Above £500

What do you like most about renewable energy usage?

What do you not like about renewable energy?

In your opinion, do you think there could be a shift from the conventional sources of energy generation such as coal/fuel oil/natural gas in about 20 years from now?

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. 15/01/2019

Energy research survey

- ○ Extremely likely
- ○ Slightly likely
- ○ Neither likely nor unlikely
- ○ Slightly unlikely
- ○ Extremely unlikely

On a scale from 0-10, how likely would you recommend renewable energy to a friend or colleague?

Not at all likely										Extremely likely
0	1	2	3	4	5	6	7	8	9	10

Rate the level of effectiveness that posters, fliers, leaflets, bill boards, television and radio adverts could have at increasing awareness on renewable energy.

- ○ Very effective
- ○ 0 Somewhat effective
- ○ 0 Neither effective nor ineffective
- ○ Somewhat ineffective
- ○ Strongly ineffective

Rate the level of effectiveness that Internet and social media could have at increasing awareness on renewable energy.

- ○ Very effective
- ○ 0 Somewhat effective
- ○ 0 Neither effective nor ineffective
- ○ 0 Somewhat ineffective
- ○ Strongly ineffective

In your opinion, if government put incentives in place for renewable energy generation/usage, will it be embraced?

- ○ Definitely yes
- ○ Probably yes
- ○ Might or might not
- ○ Probably not
- ○ Definitely not

Overall, how satisfied or dissatisfied are you with renewable energy usage?

Extremely satisfied
- ○ Somewhat satisfied
- ○ Neither satisfied nor dissatisfied
- ○ Moderately dissatisfied
- ○ Extremely dissatisfied

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C.3 Data tables for responses obtained in the energy survey conducted

Table C-1 Respondents' age

AGE (YEARS)	CHOICE COUNT (%)	CHOICE COUNT
16-25	5.88	5
25-40	57.65	49
40-65	35.29	30
Above 65	1.18	1
		85

Table C-2 showing respondents' profession/industry category

Profession	CHOICE COUNT (%)	CHOICE COUNT
Student	41.18	35
Lecturer	10.59	9
Operator	4.71	4
Manager	7.06	6
Government	1.18	1
Others	35.29	30
		85

Table C-3 Degree/qualification of respondents

Degree/qualification	CHOICE COUNT (%)	CHOICE COUNT
PhD	24.71	21
Master	50.59	43
First degree	14.12	12
GCSE	3.53	3
Other	7.06	6
		85

Table C-4 Energy type

Energy type	CHOICE COUNT (%)	CHOICE COUNT
Renewable	10.59	9
Non-renewable	40	34
Combination of non –renewable and renewable	49.41	42
		85

Table C-5 Involvement in renewable energy generation

Involvement in renewable energy generation	CHOICE COUNT (%)	CHOICE COUNT
Definitely yes	26.19	22
Probably yes	5.95	5
Might or might not	15.29	13
Probably not	23.81	20
Definitely not	29.76	25
		85

Table C-6 Renewable energy usage

Involvement in renewable energy usage	CHOICE COUNT (%)	CHOICE COUNT
Definitely yes	30.59	26
Probably yes	20	17
Might or might not	12.94	11
Probably not	21.18	18
Definitely not	15.29	13
		85

Table C-7 Level of primary renewable energy activity

Level of primary renewable energy activity	CHOICE COUNT (%)	CHOICE COUNT
Micro generation	14.12	12
Macro generation	7.06	6
Transmission	2.35	2
Distribution	1.18	1
User	51.76	44
Not applicable	23.53	20
		85

Table C-8 Frequency of renewable energy usage

Frequency of renewable energy usage	CHOICE COUNT (%)	CHOICE COUNT
Less than 4 days per week	17.65	15
4 or more days per week	18.82	16
2-3 times per month	14.12	12
Once every 2-3 months	5.88	5
Once every 6 months	4.71	4
Once per year	4.71	4
Never	34.12	29
		85

Table C-9 Energy price

Energy Price (£)	CHOICE COUNT (%)	CHOICE COUNT
0-50	32.14	27
51-100	42.86	36
101-200	20.24	18
201-500	2.38	2
Above 500	2.38	2
		85

Table C-10 Renewable energy area for exploration

Renewable energy area for exploration	CHOICE COUNT (%)	CHOICE COUNT
Biomass	14.12	12
Geothermal	1.18	1
Marine Power	1.18	1
Solar Power	49.41	42
Wind power	8.24	7
Not applicable	25.88	22
		85

Table C-11 Reason for renewable energy exploration

Reason for renewable energy exploration	CHOICE COUNT (%)	CHOICE COUNT
Cost reduction	34.12	29
Revenue generation	11.76	10
Greener environment	54.12	46
		85

Table C-12 Awareness level on renewable energy technologies (RETs)

Awareness level of RETs (posters, television, fliers, leaflets, bill boards)	CHOICE COUNT (%)	CHOICE COUNT
Very effective	27.38	23
Somewhat effective	53.57	45
Neither effective nor ineffective	16.47	14
Somewhat ineffective	3.57	3
Strongly ineffective	0	0
		85

Table C-13 Level of effectiveness of internet and social media

Level of effectiveness of internet and social media	CHOICE COUNT (%)	CHOICE COUNT
Very effective	48.19	40
Somewhat effective	40	34
Neither effective nor ineffective	10.84	9
Somewhat ineffective	1.2	1
Strongly ineffective	1.2	1
		85

Table C-14 Level of shift from conventional sources of energy generation

Shift from conventional sources of energy generation	CHOICE COUNT (%)	CHOICE COUNT
Extremely likely	51.76	44
Slightly likely	35.29	30
Neither likely nor unlikely	10.59	9
Slightly unlikely	0	0
Extremely unlikely	2.35	2
		85

Table C-15 Likely impact of incentives on renewable energy generation

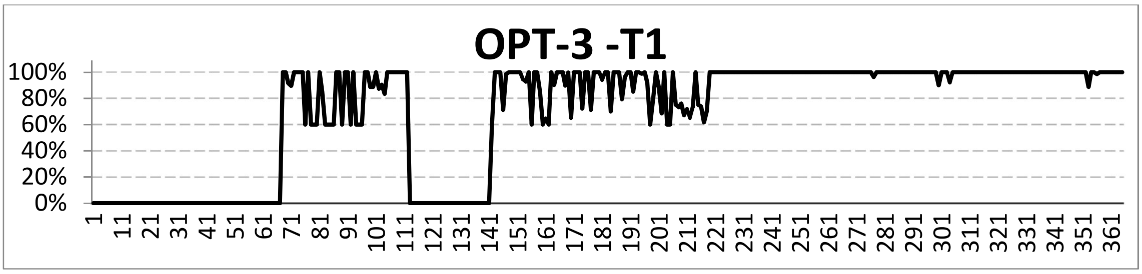
Incentives on renewable energy generation	CHOICE COUNT (%)	CHOICE COUNT
Definitely yes	48.81	41
Probably yes	38.82	33
Might or might not	10.71	9
Probably not	0	0
Definitely not	2.38	2
		85

Table C-16 Satisfaction received from renewable energy usage

Satisfaction/dissatisfaction with renewable energy usage	CHOICE COUNT (%)	CHOICE COUNT
Extremely satisfied	18.07	15
Somewhat satisfied	40	34
Neither satisfied nor dissatisfied	32.53	27
Moderately dissatisfied	7.23	6
Extremely dissatisfied	3.61	3
		85

Appendix D

D.1 Turbines 1 to 6. Normalized operating load profiles for OPT-3 solutions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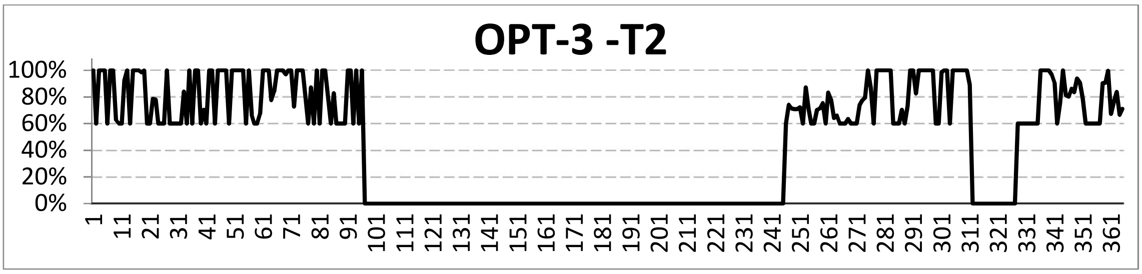
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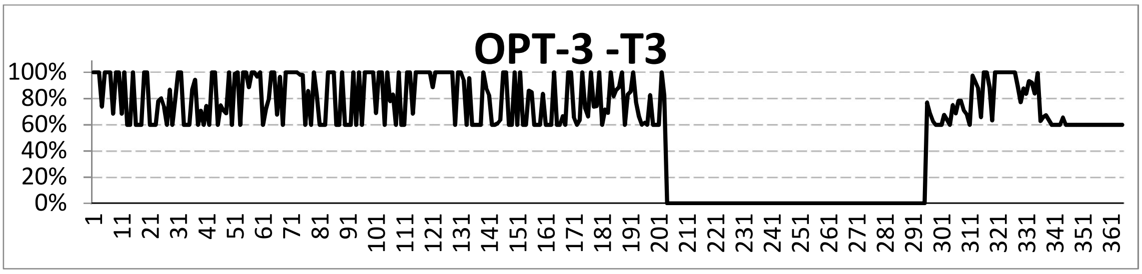
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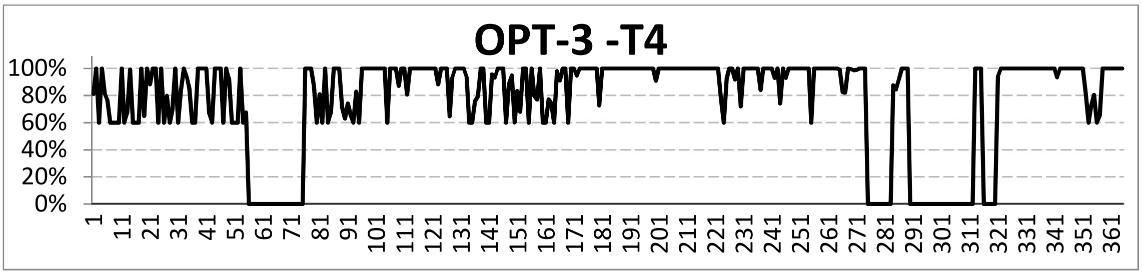
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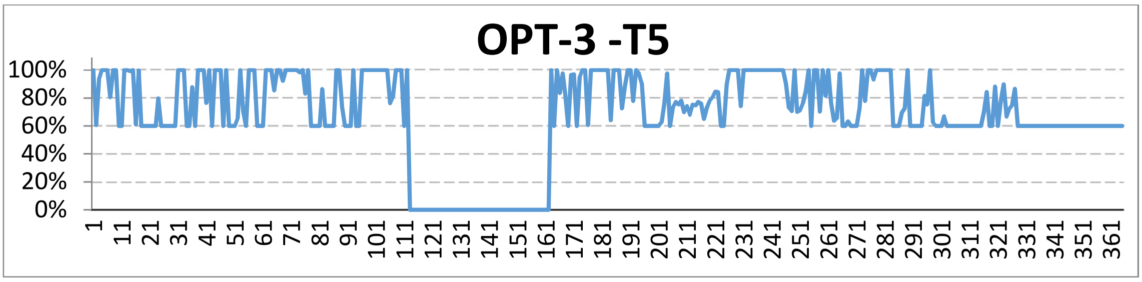
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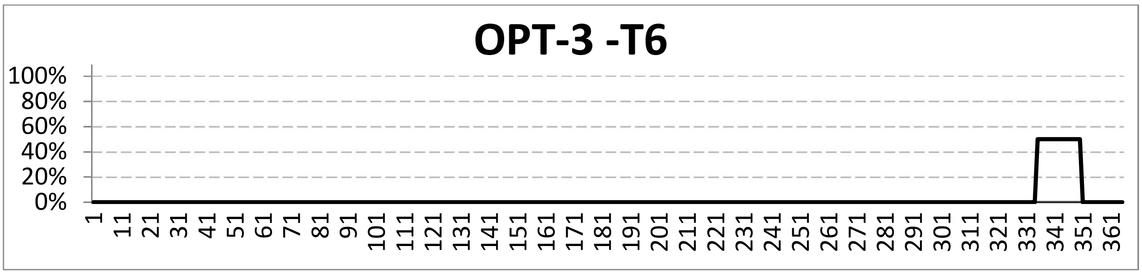
OPT-3 -T6
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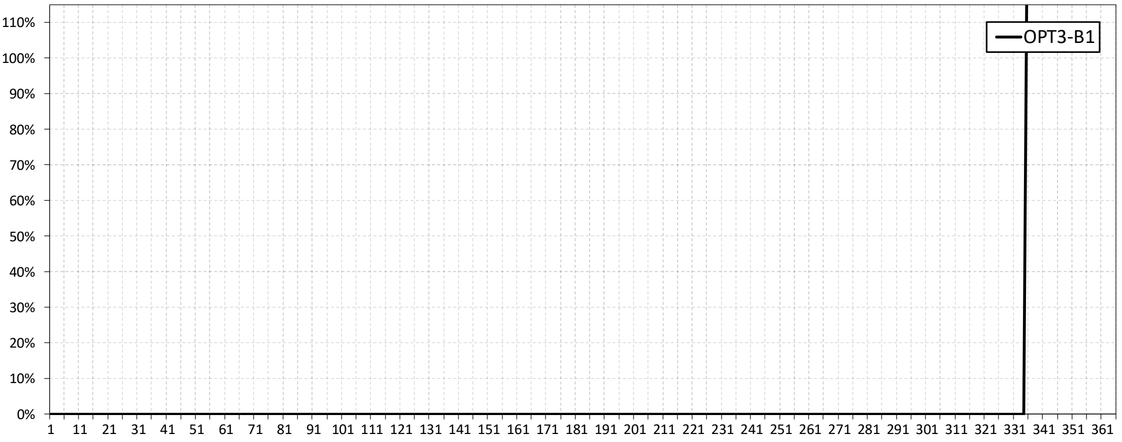
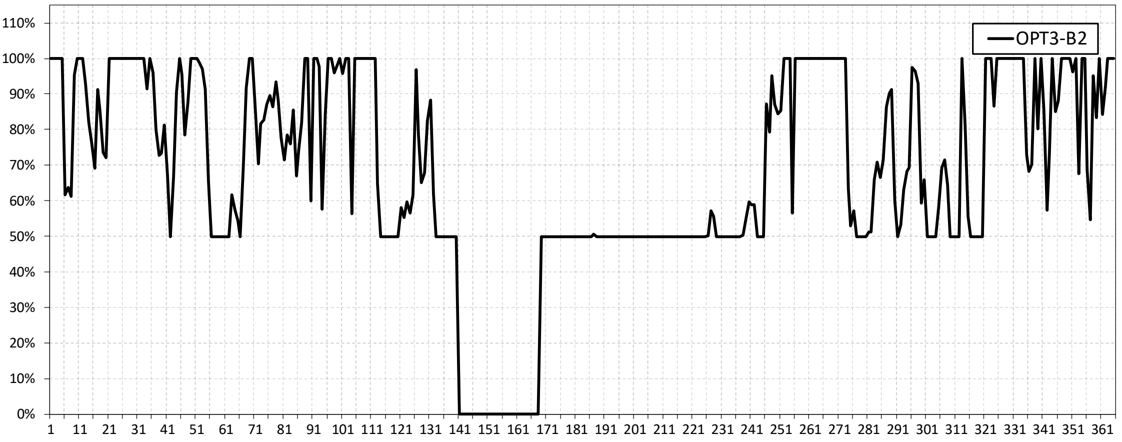
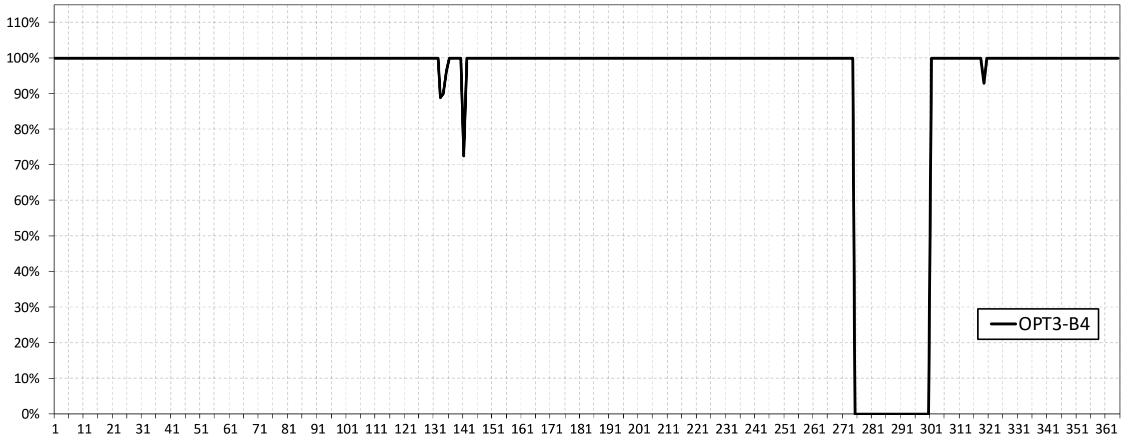
D.2 Boilers 1 to 7. Normalized operating load profiles for OPT-3 solutions



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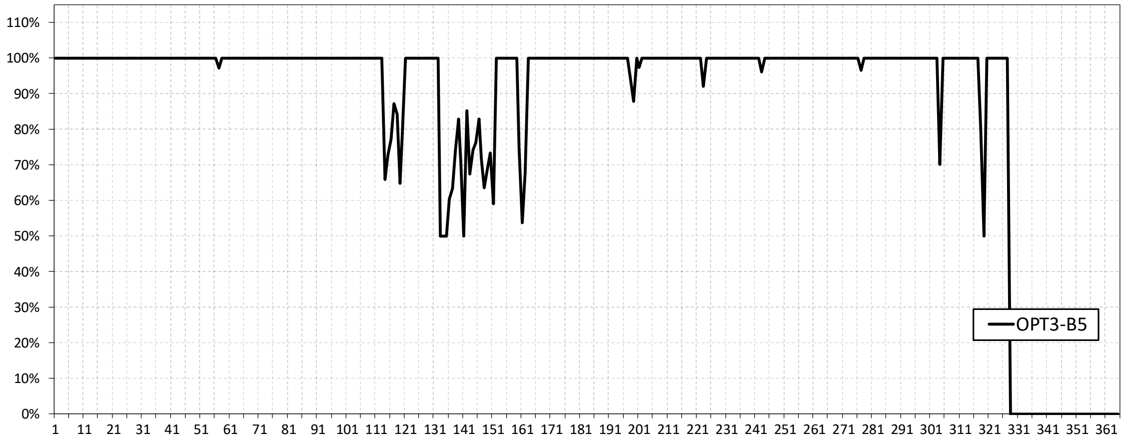
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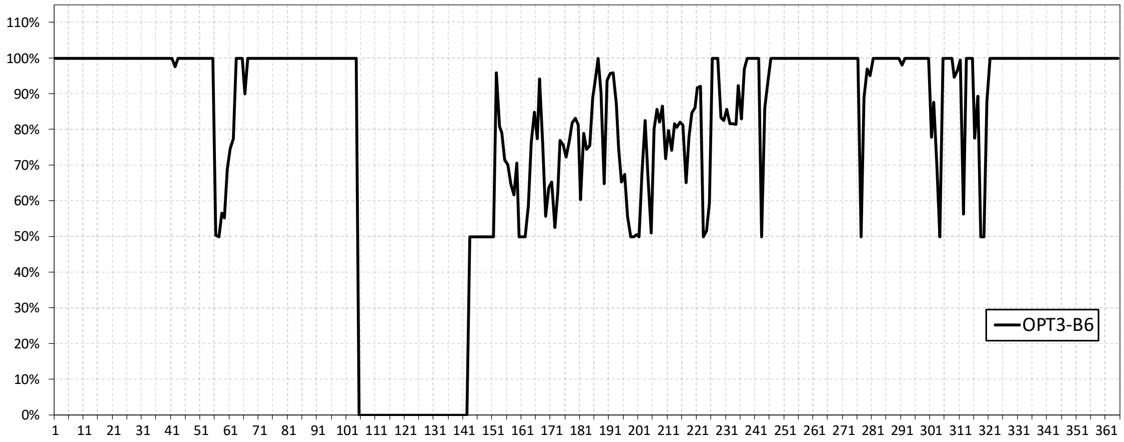
OPT3-B5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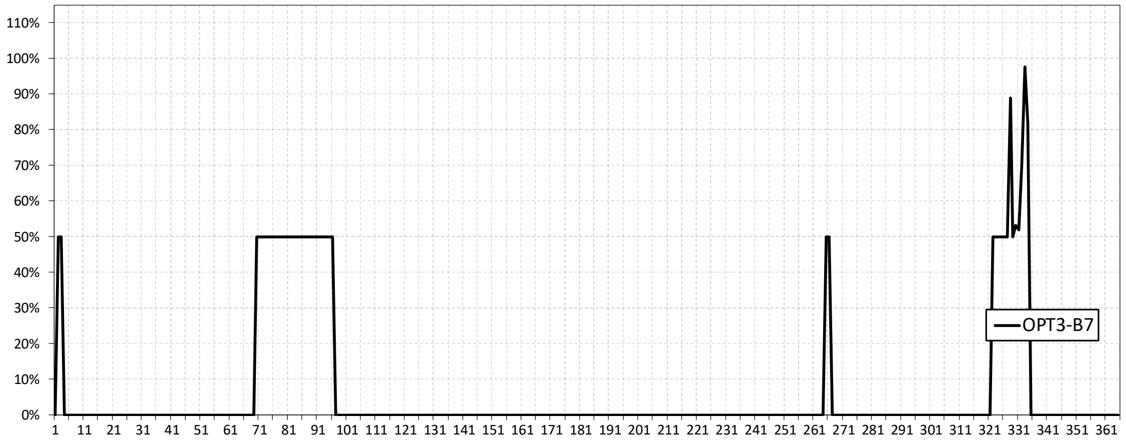
OPT3-B6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OPT3-B7

D.3 Parameter values for the case study of Karaganda utility systems

Parameters (Greek symbols)		Value
$\alpha_{(i,t)}$	startup cost for unit i in time period t (\$)	3230 (Boiler); 916 (Turbine)
β_t^E	factor for internal electricity requirements of the plant in time period t(%)	12.5
β_t^H	factor for internal heat requirements of the plant in time period t (%)	2
γ_i	number of time periods before the beginning of the current time horizon that unit i has been continuously operating since its last startup (days)	See Appendix A.2
δ_i	maximum runtime for unit i (continuous operation from its startup) (days)	25 (Boilers) 45 (Turbines)
$\Delta\varepsilon_{(i,t)}^+$	maximum operating level for the upper extreme operating region of turbine unit $i\epsilon I^T$ in time period t (MW)	See table 3-1
$\Delta\varepsilon_{(i,t)}^-$	minimum operating level for the lower extreme operating region of turbine unit $i\epsilon I^T$ in time period t (MW)	See table 3-1
$\varepsilon_{(i,t)}^{max}$	maximum operating level for the desired operating region of turbine unit $i\epsilon I^T$ in time period t (MW)	See table 3-1
$\varepsilon_{(i,t)}^{min}$	minimum operating level for the desired operating region of turbine unit $i\epsilon I^T$ in time period t (MW)	See table 3-1
ζ_t^{el}	electricity demand in time period t (MWh)	See figure 3-3
$\zeta_{(j,t)}^{heat}$	heat demand for heat network j in time period t (MWh)	See figure 3-3
$\eta_{(i,t)}$	efficiency for turbine unit $i\epsilon I^T$ and boiler units $i\epsilon I^B$ in time period t (%)	64-75 (Boiler); 35-60 (Turbine)
η_j^{RCU}	heat efficiency factor for reduction cooling unit	10

	associated to heat network j (%)	
$\theta_{(i,t)}^{max}$	maximum heat generation level for boiler unit $i \epsilon I^B$ in time period t (MW)	290.6 (Boilers 1 to 7); 464.9 (Boiler 8)
$\theta_{(i,t)}^{min}$	minimum heat generation level for boiler unit $i \epsilon I^B$ in time period t (MW)	145.3 (Boilers 1 to7); 231.3 (Boiler 8)
$\theta_{(i,t)}^{Tmax}$	maximum outlet heat flow from turbine $i \epsilon I^T$ in time period t (MW)	See table 3-1
$\kappa_{(i,t)}$	maintenance cost for unit i if maintenance starts in time period t (\$)	See table 3-2
λ_t^{buy}	cost for acquiring electricity from externals sources in time period t (\$)	See Appendix A.2
λ_t^{ex}	cost for excessive electricity generation in time period t (\$)	See Appendix A.2
$\mu_{(j,t)}^{buy}$	cost for acquiring heat from externals sources for heat network j in time period t (\$)	See Appendix A.2
$\mu_{(j,t)}^{ex}$	cost for excessive heat sent (i.e., disposed heat) to heat network j in time period t (\$)	See Appendix A.2
M	a large number	1000000
ν_i	duration of maintenance task for unit i (days)	See Table 3-2
$\xi_{(i,t)}$	fuel cost for boiler unit i in time period t (\$/ton)	6
$\pi_{(i,t)}$	fixed operating cost for unit i in time period t (\$)	See Appendix a.2
$\rho_{(i,t)}^{+}$	penalty for turbine $i \epsilon I^T$ for operating in the upper extreme operating region	See note
$\rho_{(i,t)}^{-}$	penalty for turbine $i \epsilon I^T$ for operating in the lower extreme operating region	See note
τ_i^{max}	latest starting time for the maintenance task of unit i (i.e., upper bound of time-window) (days)	365
τ_i^{min}	earliest starting time for the maintenance task of unit i (i.e.,	1

	lower bound of time-window) (days)	
$\varphi_{(i,t)}$	shutdown cost for unit i in time period t (\$)	2,422 (Boiler); 458 (Turbine)
ψ_i	minimum idle time for unit i (from its last shutdown) (day)	1
ω_i	minimum runtime for unit i (from its last the startup) (days)	2
Cq_t	fuel calorific value in time period t (MWh)	3,980 (Gcal) * 1.16223
$loss_i$	heat losses coefficient for boiler unit $i\epsilon I^B$ (%)	2

However, The penalties ("rho +" and "rho –" are a combination of turbines priorities and the effect that operation out-of-the-desired operation region could have to each turbine. Since the plant manager knows the design and actual performance (and condition) of each turbine can decide which turbines would be more undesired to operate in extreme regions. That way, turbines that are more prone to damage or being very inefficient in extreme regions are given much higher penalties to deter their operation in extreme regions. Of course, one could choose other criteria to set these priorities accordingly.

D.4 Parameter values for the case study of integrating biomass into energy supply chain networks

Parameters (Greek symbols)		Value
$\alpha_{(r,r,p,q,t)}$	bounds on the available capacities for both conversion and transfer tasks	0 (minimum); 1 (maximum)
$\beta_{(r,s,t)}$	bounds on inventory levels on states that can be stored $s \in S^G$ (units)	0.5 (minimum); 1(maximum)
$\beta^0_{(r,s)}$	initial level of inventory for all states in all regions (units)	10,000
$\gamma_{(r,q,t)}$	bounds on allowable expansion levels for pre-processing, conversion and storage technologies	See Table 4-2
$\gamma^{TR}_{(r,r',t)}$	bounds on allowable expansion levels for transfer technologies $q \in Q^{TR}$	See Table 4-2
$\delta_{(r,q,t)}$	fixed operating cost for the total installed capacities of technology *q.(rmu)*	See Table 4-2
$\varepsilon^0_{(r,q,t)}$	initial investment cost required to establish a technology (money unit/unit)	See Table 4-2
$\varepsilon_{(r,q,t)}$	investment cost needed to expand the capacity of an already established technology (money unit/unit)	See Table 4-2

$\zeta_{(r,s,t)}$	demand for useful products states $s \in S^u$ in region r in time period *t (units)*	See Appendix B.3 (pages 214-217)
$\eta_{(r,s,t)}$	co-efficient of deterioration for states that can be stored $s \in S^G$ (%)	15
$\kappa_{(s,p,q)}$	co-efficient for input/output states for tasks that could be performed by technology q	See Appendix B.3 (pages 214-217)
$\lambda_{(r,s,t)}$	co-efficient of holding cost for storable states	0.2
$\lambda^D_{(r,s,t)}$	co-efficient of penalty for causing pollution through the disposal of unwanted substances into the environment.	0.5
$\mu_{(r,q,t)}$	time of installation for technology *q* in region *r* or the duration of constructing an additional facility, for an implementation start in period *t.(days)*	1
M	a large number	1000000
$\vartheta_{(r',r,s,p,q,t)}$	Transfer cost for states considered as useful products $s \in S^u$ to points of demand (money units)	0.25
$\pi_{(r,s,p,q,t)}$	cost of states production through conversion technology (mu)	See Table 4-2

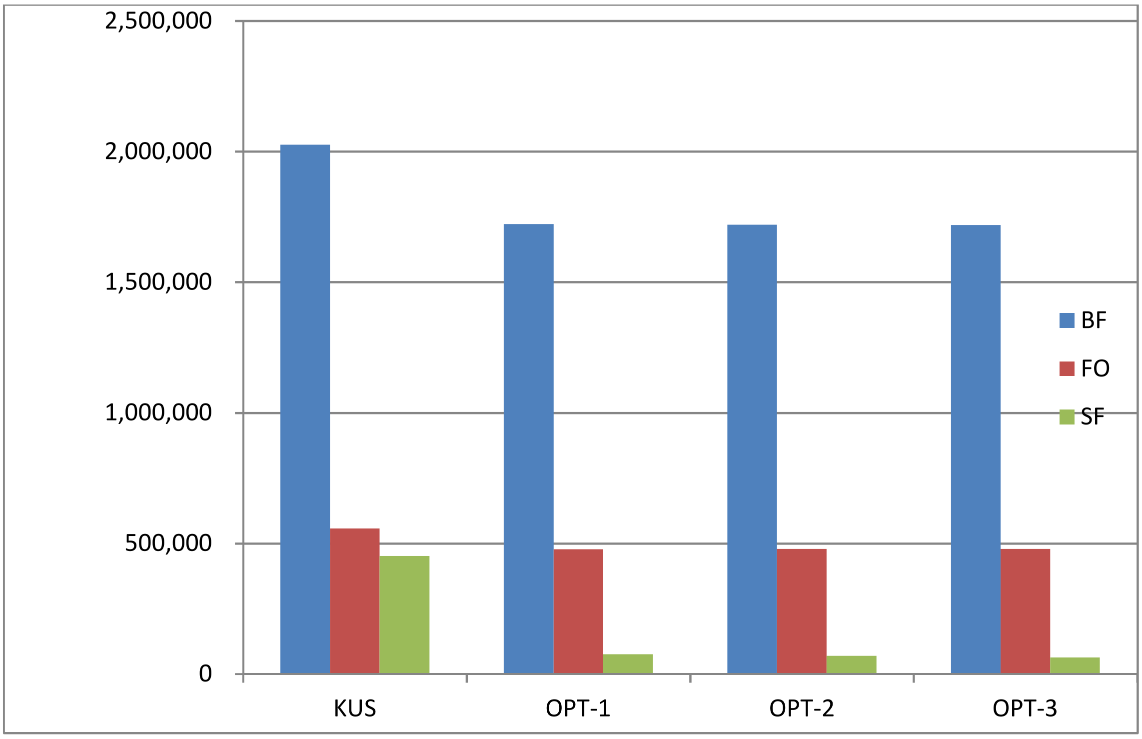
$\varphi_{(r,q)}$	Initial installed capacity for biomass/coal exploitation, $q \in Q^E$, pre-processing and conversion technologies, $q \in Q^{PRC}$ in region *r* *(units)*	10,000
$\varphi^{G}{}_{(r,s,q)}$	Initial installed capacity for storage technology $q \in Q^B$ in region *r (units)*	10,000
$\varphi^{TR}{}_{(r,r',q)}$	Initial installed capacity for transfer technology $q \in Q^{TR}$ that connects two regions (units)	10,000
$\psi_{(r,s,p,q,t)}$	raw material cost money (units)	50
$\omega_{(r,s,t)}$	maximum available amount of raw material (units)	500

Appendix E

E.1 Cost comparison for KUS, OPT-1,OPT-2 and OPT-3 solution approaches

	KUS		OPT-1		OPT-2		OPT-3	
Boiler Fuel BF)	**2025550.688**	**56.3%**	**1722348.424**	**60.6%**	**1719639**	**60.7%**	**1718183**	**60.8%**
Fixed Operating (FO)	**557680**	**15.5%**	**477600**	**16.8%**	**479040**	**16.9%**	**479080**	**17.0%**
Startup/Shutdown (SF)	**452186**	**12.6%**	**75944**	**2.7%**	**69320**	**2.45%**	**64070**	**2.27%**
Maintenance	**564194**	**15.7%**	**564194**	**19.9%**	**564194**	**19.9%**	**564194**	**20.0%**
	3599610.688	**100.0%**	**2840086.424**	**100.0%**	**2832193**	**100.0%**	**2825527**	**100.0%**

	KUS	OPT-1	OPT-2	OPT-3
BF	**2,025,551**	**1,722,348**	**1,719,639**	**1,718,183**
FO	**557,680**	**477,600**	**479,040**	**479,080**
SF	**452,186**	**75,944**	**69,320**	**64,070**
MAIN	**564,194**	**564,194**	**564,194**	**564,194**
	3,599,611	**2,840,086**	**2,832,193**	**2,825,527**
	TOTAL REDUCTION	**759,524**	**767,417**	**774,084**
	TOTAL REDUCTION (%)	**21.1%**	**21.3%**	**21.5%**
	SF	**83.2%**	**84.7%**	**85.8%**
	FO	**14.4%**	**14.1%**	**14.1%**
	BF	**15.0%**	**15.1%**	**15.2%**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OPT-2
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