Use of Challenging fuels for the UK Low-Carbon Energy Transition

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Opening New Fuels

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Outline

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- Biomass combustion technologies
- Comparison of Biomass combustion technologies based on performance criterion
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- Unit Commitment and Economic Dispatch (UCED) Model
- Conclusions

Introduction

- **Biomass combustion** is a cost-effective way to contribute to achieve **greenhouse gas emission reduction** targets and to increase the **share of renewable energy** sources in low-carbon energy systems.

- Biomass plants will contribute to **security of electricity supply and provide flexible energy generation**.

- **Challenging fuels**, such as waste wood from municipal, commercial, industrial construction and demolition waste streams, can be used to **decarbonise the energy and industrial sectors**, contribute to more **diversified fuel chain** and **reduce carbon impact of waste management**.

- **Bioenergy with Carbon Capture and Storage (BECCS)** promotes the net removal of CO_2 from the atmosphere (negative emission technology). A milestone from 2030 to 2050 would require one out five biomass fired power plant to be equipped with CCS [1,2]

Introduction

Biomass feedstock

Woody biomass and wood waste

- Availability and security of supply
- Thermal properties & composition

Combustion Technologies

- Existing or new build plant
- Electricity or Co-generation (CHP)
- Capacity & Efficiency
- Biomass fuel characteristics

Investment decisions & Operation Strategies for Biomass plants deployment

Regulations, Policy incentives & support mechanisms

- Regulations & taxes on CO_2 emissions (EPS, CFP)
- Incentives on Feedstock, generation and market (e.g. ROCs, FIT, CFD, CM)

Reduce uncertainty for investment in renewable energy

Technical analysis

- Models based on fundamental principles and experimental work
- Practical experience

Opportunities in the UK

Existing and planned biomass co-firing and dedicated power plants and CHP

Economic analysis

- Unit Commitment and Economic Dispatch (UCED) models

Biomass combustion options

Direct co-firing

- Biomass is milled and fed to the furnace using **existing coal mills and combustion system** (a),
- **Dedicated biomass milling system** (b) **and biomass burners** (b), biomass is milled to sizes suitable for suspension firing and is injected into new/modified burners.

Indirect co-firing (c)

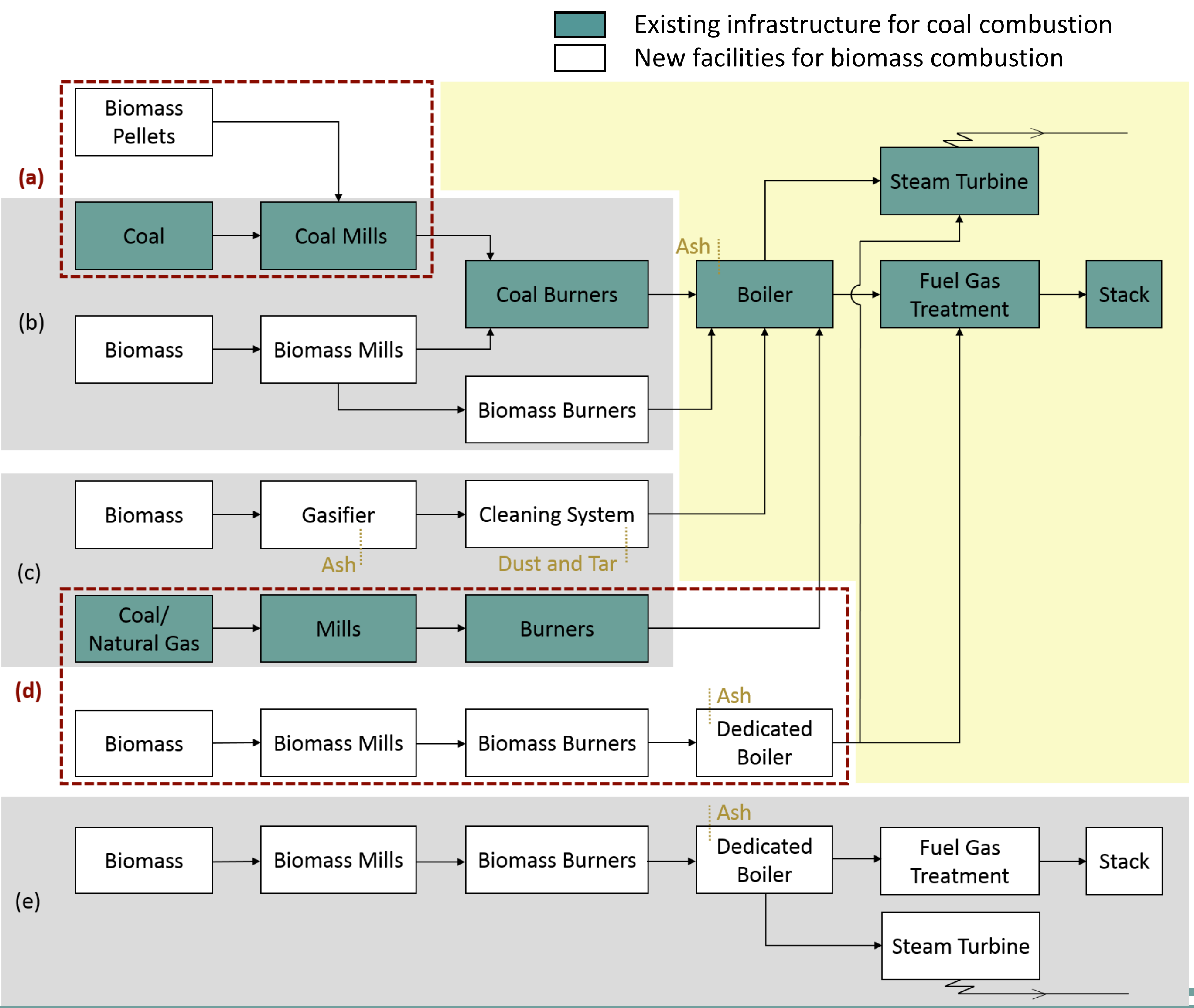
- Gasification of solid biomass in a gasifier. Syngas is fired in the existing boiler or in a dedicated boiler.

Parallel co-firing (d)

- A new dedicated boiler is installed to produce steam used in the coal- or gas-fired power plant.

Dedicated biomass firing(e)

- A new dedicated biomass plant is constructed.



Biomass combustion options

Options		Plant Efficiency	Operation Experience	Biomass Fuel Flexibility	Security of Supply	Ash Deposition	Emissions	Capital Cost	Development Status
(a)	Direct	Reduced (for moderate co-firing levels)	High (large-scale application)	Low (limited level of co-firing; lack of fuel flexibility)	Suited (if there are uncertainties for security of biomass supply)	Ash deposition (e.g., slagging and fouling, corrosion)	Lower SO_2, NO_x and CH_4 (lower sulphur and nitrogen content in biomass; avoided CH_4 from landfills)	Low (existing infrastructure)	Commercial [3]
(b)	Direct	Reduced (for moderate co-firing levels)	High (large-scale application)	Low (higher level of co-firing than (a); lack of fuel flexibility)	Suited (if there are uncertainties for security of biomass supply)	Ash deposition (e.g., slagging and fouling, corrosion)	Lower SO_2 and NO_x (lower sulphur and nitrogen content in biomass)		mmercial [3]
(c)	Indirect	Reduce 10% c	o- g	Moderate (higher level of co-firing than (a)-(b); wide range of biomass; flexible use of gas fuel, e.g., coal, oil, gas)	Partially unsuited (part of the plant depends on biomass supply)	Reduced boiler slagging (biomass is not directly fed into the boiler)	Yet to be determined [4]	gas cleaning and filtering equipment)	Demonstration [3]
(d)	Parallel	Reduced (by 1.5% at 10% co-firing [5]; optimal efficiency of each fuel can be chosen)	Low (lack of experience with co-firing and testing [5])	High (higher co-firing ratios than (a)-(c); flexible use of problematic fuels with high alkali and chlorine contents)		omass-related deposition aration of the ashes)	Less (serves as a gas-over firing designed to minimise NO_x [6,7])	Higher than (a)-(c) (additional infrastructure is needed)	Early Commercial [3]
(e)	Dedicated	Optimal efficiency (new plant)	High (small-scale application)	High (flexible use of problematic fuels with high alkali and chlorine contents, e.g., wheat straw)	Unsuited (fuel supply depends 100% on fuel supplier)	Only biomass ash deposition	Net CO_2 emissions (offers the option for negative CO_2 emissions)	High (new installation)	Commercial (steam Rankine cycle [3])

Larger operation experience for direct co-firing

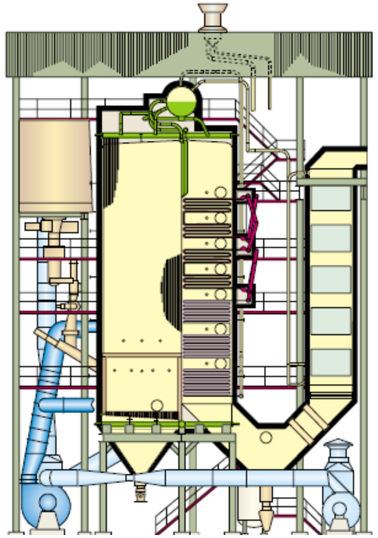
Can be used to burn a wider range of fuels

Lower capital investment for direct co-firing

Biomass combustion technologies

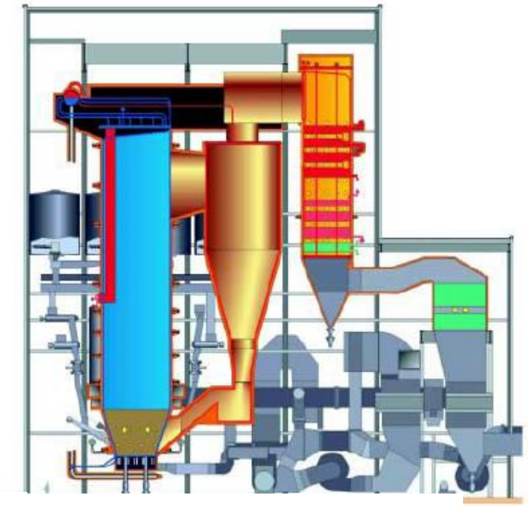
In addition to Pulverised Fuel Systems (PFS), the main combustion installations used nowadays are:

Bubbling Fluidised Bed combustion boilers **(BFB)**



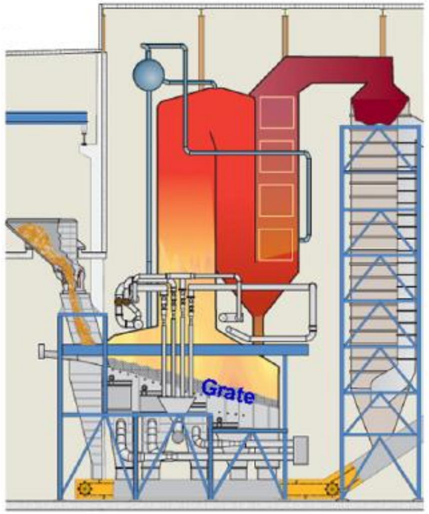
(EUBIONET 2003)

Circulating Fluidised Bed combustion boilers **(CFB)**



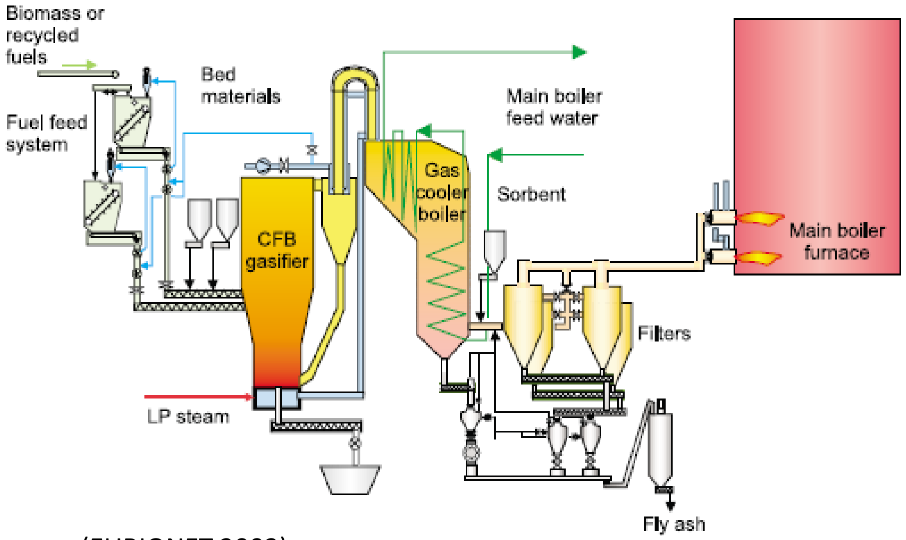
(EUBIONET 2003)

Packed Bed (PB) /
Moving-grate furnaces and underfeed stokers with rotary grates



(Yin et al. 2008)

Biomass Gasifier (GF)
(atmospheric fluidised bed gasifier with flue gas cleaning system)



(EUBIONET 2003)

Biomass combustion technologies

More favorable ▮▮▮ **Less favorable**

	Output [MW_e]	Efficiency	Biomass Fuel Flexibility	Fuel Moisture Range	Particle Size	Investment Cost
Co-firing in Pulverised Fuel System (**PFS**)	High (10-1000 MW_e [8])	High (35–40% [9] [1])	Low (fuel: sawdust and fine shavings)	Low (limited to <15 wt% [10])	Low (limited to <5 mm [8,10])	Low (cost reported <1000 USD/kW [11])
Firing in **PFS**	High (10-650 MW_e [8])	High (35–40% [9])	Low (fuel: sawdust and fine shavings)	Low (limited to <15 wt% [10])	Low (limited to <5 mm [8,10])	Moderate (cost reported <4000 USD/kW [11])
Circulating Fluidised Bed (**CFB**)	Moderate (15-300 MW_e [8])	Moderate (31.4–36.5% [10])	Moderate (fuel: bark, woodchips, sludge)	High (10-50 wt% [10])	Moderate (<72 mm [10])	Moderate (cost reported <4000 USD/kW [10])
Bubbling Fluidised Bed (**BFB**)	Moderate (5-120 MW_e [8], lower than **CFB**)	Low (28–30% [10])	High (fuel: bark, woodchips, sludge, *etc.* [2])	High (10-50 wt% [10])	Moderate (<72 mm [10])	High (cost reported <5000 USD/kW [10])
Packed Bed – Grater (**PB**)	Moderate (0.15 - 150 MW_e [8])	Moderate (30–35%)	High (fuel: wide range of biomass)	High (10-50 wt% [10])	High (<150 mm [8])	High (cost reported <5000 USD/kW [10])
Gasifier (**GF**)	Low (<20 MW_e [10])	Low (25–30%)	Moderate (fuel: sludge, woodchips, rice hulls)	High (15-50 wt% [10])	High (<100 mm [10] – lower than **PB**)	High

[1] The levels of efficiency can be maintained in case of small co-firing ratios. Power plants with power output <50 MW_e and either firing or co-firing biomass with coal have efficiencies 25-30% [9].
[2] Biomass fuel in BFB: bark, woodchips, sludge, bagasse, low alkali content fuels, mostly wood residues with high moisture content.
Note: Colours, from light green (**low value**) to dark green (**high value**), indicate the performance of the common biomass combustion technologies based on identified key features.

Biomass combustion technologies

More favorable → **Less favorable**

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Packed Bed – Grater (**PB**)	Moderate (0.15- 150 MW_e [8])	Moderate (30–35%)	High (fuel: wide range of biomass)	High (10-50 wt% [10])	High (<150 mm [8])	High (cost reported <5000 USD/kW [10])
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Larger size and efficiency are possible with PFS Yet dedicated biomass plants might benefit from smaller scale to ensure fuel supply

Co-firing and firing in PFS present smaller investment cost, yet a pre-treatment of the biomass is required

CFB, BFB, PB, GF can be used to burn a wider range of biomass fuels (HHV, moisture, volatiles and ash content, and particle size)

Comparison of combustion technologies based on performance criterion

Qualitative analysis: (++), Exceeds Requirements; (+), Meets Requirements; and (–), Less Favourable.

Performance Criterion	Co-firing in PFS	Firing in PFS	Firing in CFB	Firing in BFB	Firing in PB	Firing in GF
Economic-related Criteria						
Investment cost	++	+	+	–	–	–
O&M cost	[illegible]	–	[illegible]	[illegible]	++	+
Emission-related Criteria						
Pollutant gas emissions	–	+	++	++	++	++
Ash deposition	–	++	++	++	++	++
Fuel-related Criteria						
Fuel flexibility and availability	+	–	++	++	++	++
Fuel pre-processing	–	–	++	++	++	++
Operation-related Criteria						
Operational experience	++	++	[illegible]	[illegible]	[illegible]	–
Global market	++	++	++	–	++	–
Load response/flexibility	–	–	++	++	–	–
Plant-related Criteria						
Plant efficiency	++	++	[illegible]	[illegible]	[illegible]	[illegible]
Thermal fuel input	++	++	[illegible]	[illegible]	[illegible]	[illegible]
Retrofit for CCS	++	++	++	+	+	+
EfW and CHP	–	–	++	++	++	+

Higher risk of slagging, fouling and corrosion

Ash is separated in the boiler and risks are reduced

Can accept a wide range of biomass fuels and allow the combustion of untreated biomass fuels

PFS present higher efficiency for power generation, Yet CFB, BFB and Grate boilers are preferable for CHP, achieving high overall efficiencies

UK policy incentives and support mechanisms

GHG emissions reduction:

- ***EU Emission Trading System***
- ***Renewable Energy Directive*** (2009/28/EC)
- ***Energy Efficiency Directive*** (2012/27/EU)

Energy recovery from waste:

- ***Landfill of waste Directive*** (1999/31/EC)

Biomass Power and CHP plants must comply with:

- ***Industrial Emissions Directive*** (IED 2010/75/EU) establishes limit values on industrial pollutant emissions (including large combustion plants >50MWe)
- ***Waste Incineration Directive*** (WID within IED Annex VI) applies to facilities burning "treated" wood wastes, i.e. Grade C and D.

- ***Carbon Price Floor, CPF*** (aims to ensure Carbon price at a level that drives low carbon investment)
- ***Emissions Performance Standard, EPS*** (sets emissions level limits at 450 gCO_2/kWh for new plants or boilers > 50MWe)
- ***Levy Control Framework, LCF*** (designed to control the costs of supporting low carbon electricity)

Policy incentives:

Generation & Market

- ***Renewable Obligation Certificates*** (ROCs), 2002
  Banded in 2009. Closed to new generation in 2017
- ***Feed in Tariff*** (FIT), 2010
- ***Renewables Heat Incentives*** (RHI), 2011

Electricity Market Reform (EMR) in 2013

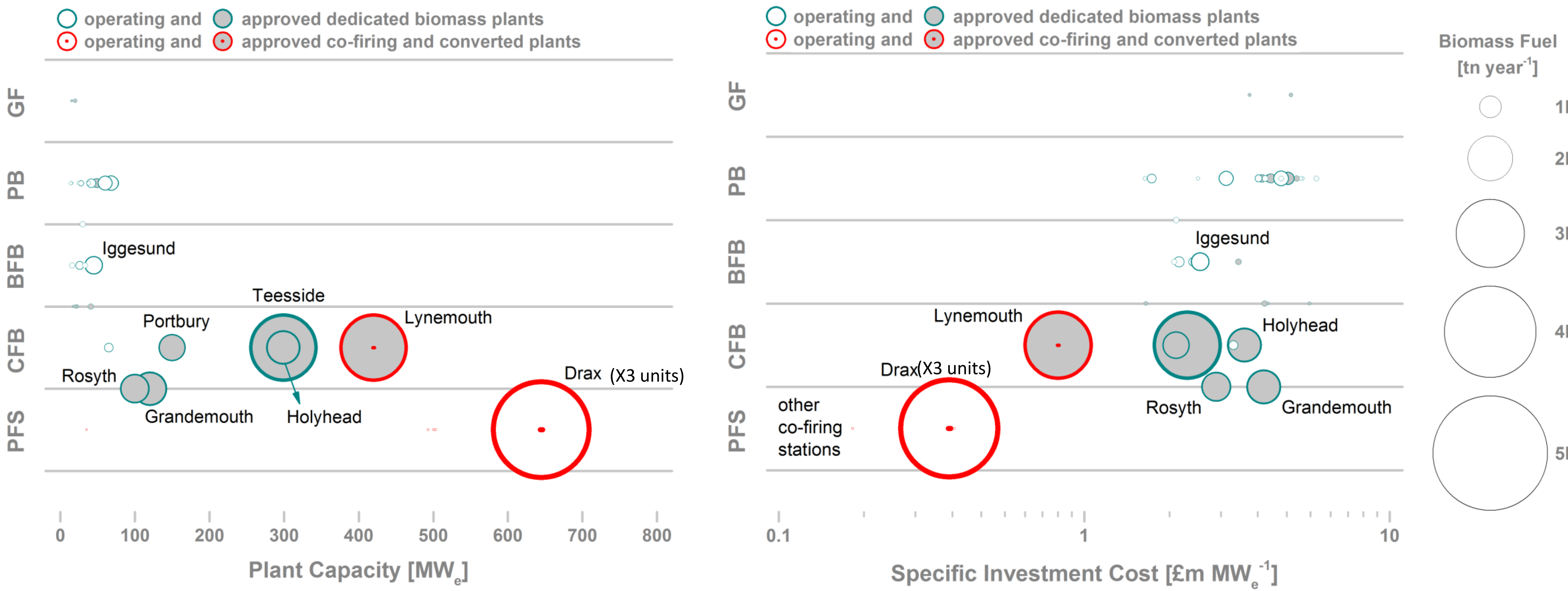
- ***Feed in Tariff*** (FIT) up to 5 MWe
- ***FITs Contract for Difference*** (CFD) ->
  100% biomass CHP plants
- ***Capacity Market*** (CM)

Feed stocks

- ***Energy Crop Scheme*** (ECS)
- WRAP covers ***waste gate fees*** for a range of waste fuels

Biomass fuel opportunities for energy generation in the UK

Existing and planned biomass plants for Power and Co-generation



Biomass fuel opportunities for energy generation in the UK

Existing and planned biomass only plants for Power generation and Co-generation

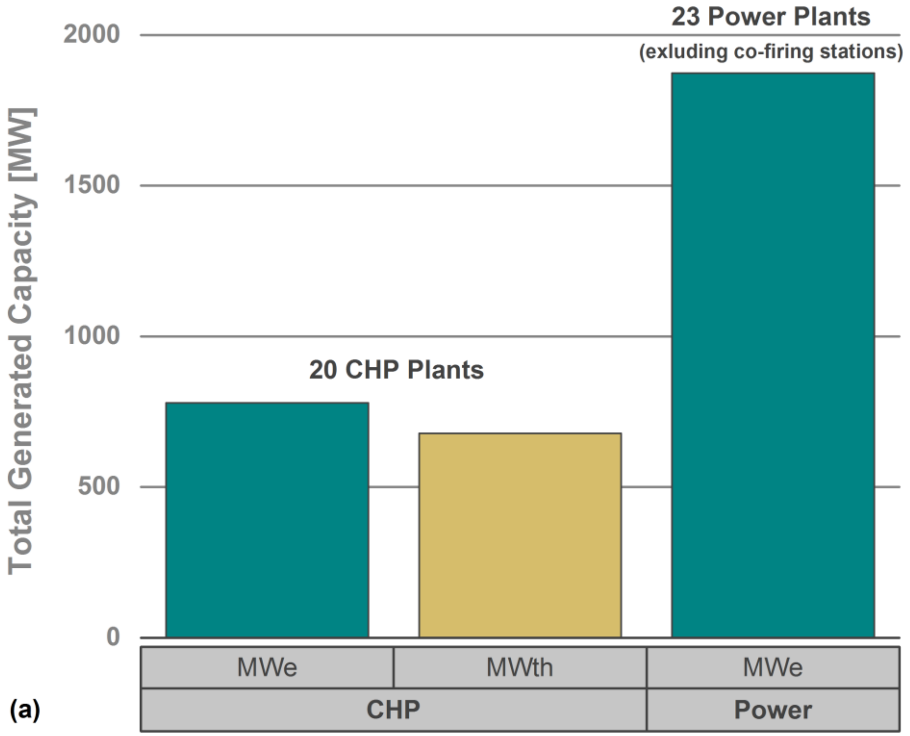


Figure 2. Total power (MW_e) and thermal (MW_{th}) installed capacity for dedicated biomass **CHP** and **power plants**

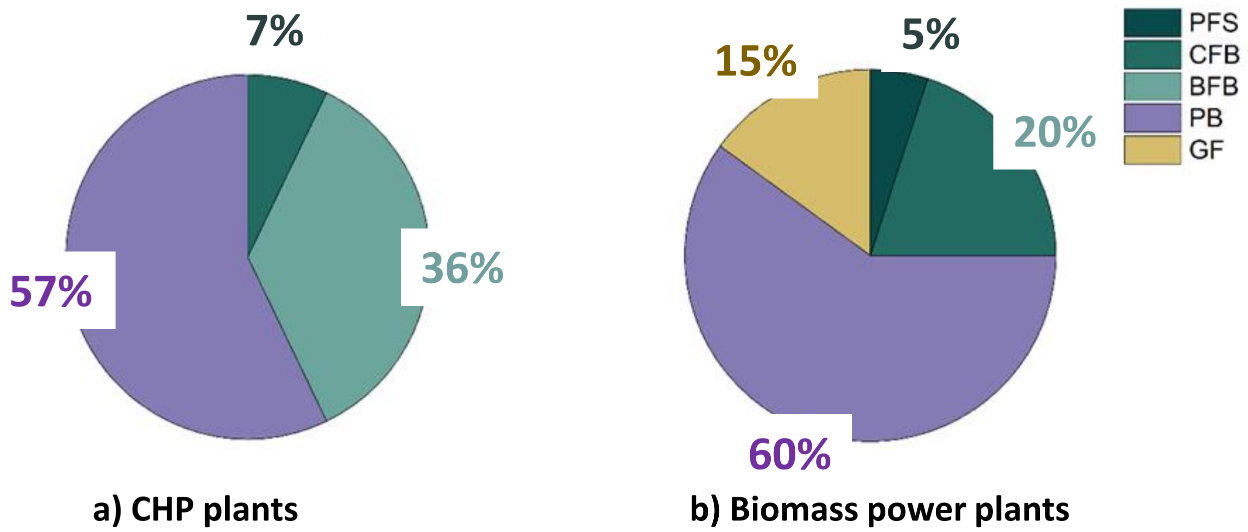


Figure 3. Type and proportion of combustion technologies used for dedicated biomass **CHP** and **power plants**

Biomass fuel opportunities for energy generation in the UK

Biomass fuel: waste wood

- **Waste wood** resources can provide an **alternative energy feedstock**, increases fuel diversity and minimises waste disposal to landfill.

- **Waste wood represents between 10% and 34.4% of the solid biomass** burnt in the UK. The percentage depends on the plant thermal input and the combustion technology.

- In the UK, more than 20 power stations (> 20 MW_e) use waste wood, either alone or in combination with clean white wood.

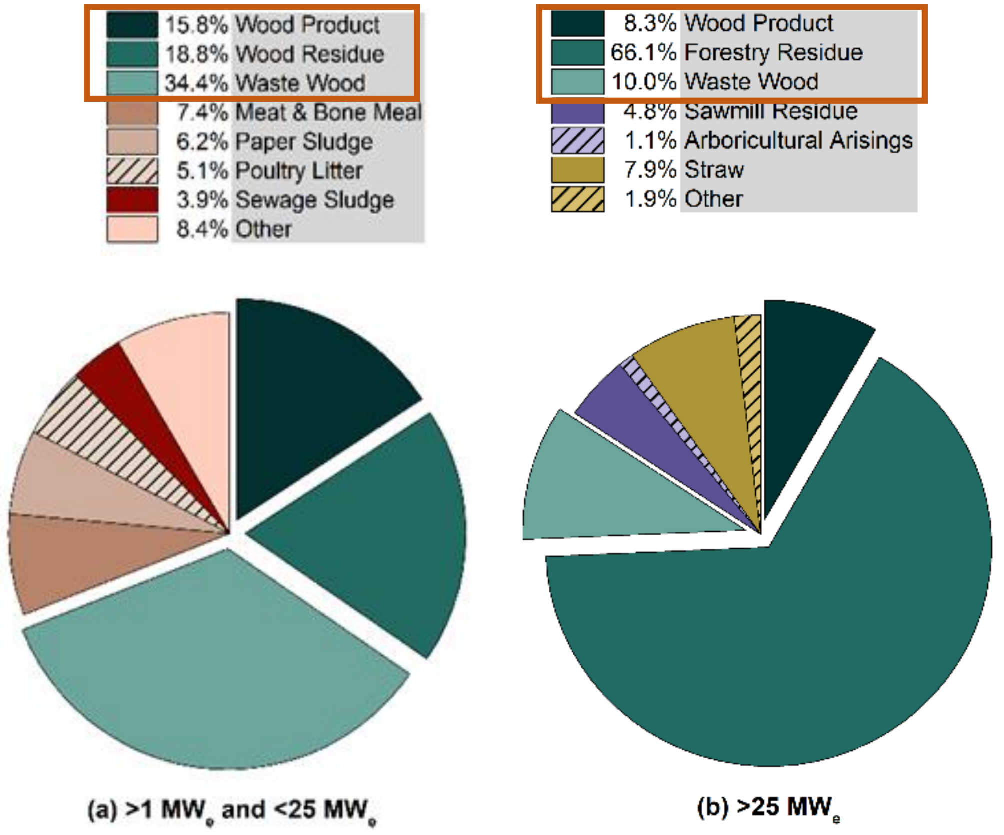


Figure 4. Type and proportion of solid biomass used in direct combustion stations: **(a)** greater than 1 MW_e but less than 25 MW_e and **(b)** greater than 25 MW_e. Source: [13].

Biomass fuel opportunities for energy generation in the UK

Existing and planned plants firing and co-firing waste wood

- ▪ *Chilton Biomass ,* CHP 17.56 MW_e + 45 MW_{th}
- ▪ *Wilton 10 Power Station,* CHP BFB, 34 MW_e + 10 MW_{th}
- ▪ *Ridham Dock Biomass plant,* CHP Grate boiler, 25 MW_e + 75 MW_{th}
- ▪ *Ferrybridge Multi-Fuel Plant 2,* PB Grate boiler, 70 MW_e
- ▪ *Tilbury Green Power Facility,* PB Grate boiler, 60 MW_e
- ❑ *Tasterne Biomass Plant,* FB, 22 MW_e
- ❑ *Port Clarence Biomass Plant 2,* CHP PB Grate boiler, 40 MW_e
- ❑ *Templeborough Biomass power plant,* CHP PB Grate boiler, 41 MW_e
- ❑ *Widness CHP Plant,* CHP PB Grate boiler, 20 MW_e + 7.8 MW_{th}
- ❑ *Holyhead Biomass Power Plant,* CHP CFB GF, 299 MW_e
- ❑ *NEC Birmingham,* CHP FB, 17 MW_e + 20 MW_{th}.
- ❑ *Trewcn Biomass plant,* CHP BFB, 25 MW_e + 2 MW_{th}
- ❑ *Margam Green Energy Plant #2,* CHP Grate boiler 42 MW_e + 9 MW_{th}
- ❑ *Fiddlers Reach Biomass Plant,* CHP GF, 15 MW_e
- ❑ *Portbury Biomass-Fired Energy Plant,* CFB, 150 MW_e

▪ In operation ❑ Approved

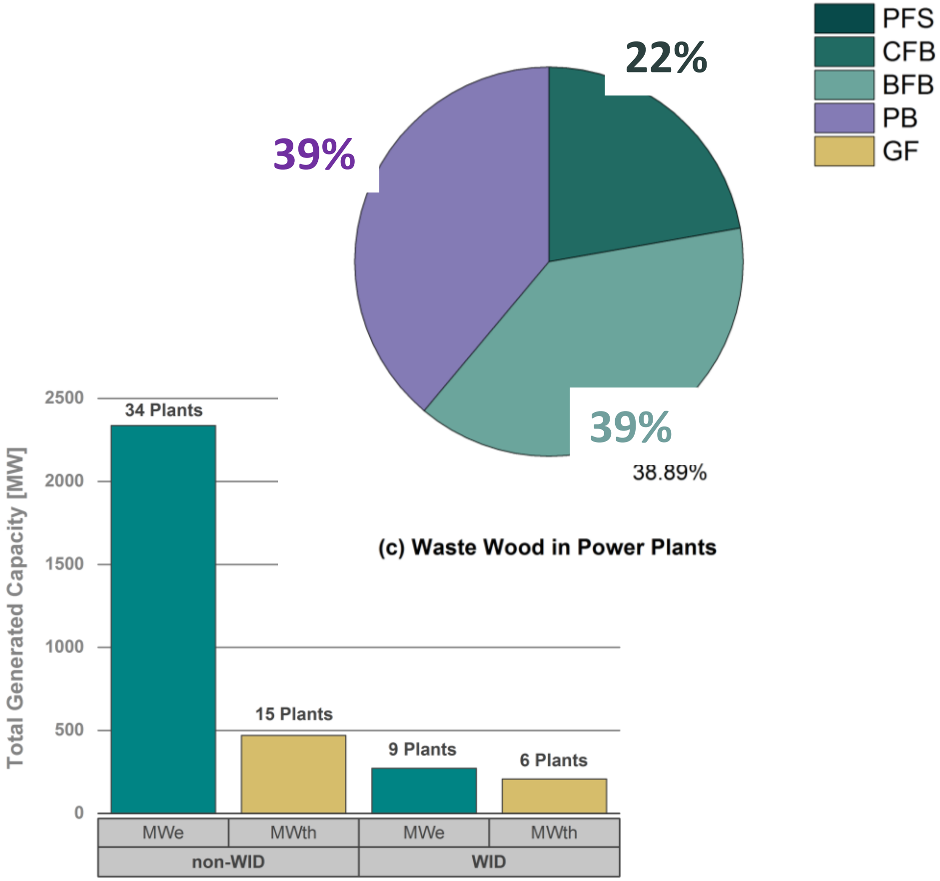


Figure 5. Total power (MW_e) and thermal (MW_{th}) installed capacity for **non-WID** and **WID complaints**.

Unit Commitment and Economic Dispatch (UCED) Model

UCED is a mathematical model that optimises the operation of a power system with minimum system cost over a specified period

<u>Inputs</u> to the model

<u>Operational</u> characteristics of generators

Power ***<u>system</u>*** characteristics

<u>Model</u> set up

- **<u>Conventional</u> power plants** (incl. biomass and renewables)
  - number of each type of plants
  - installed capacity
  - availability factors
  - min & max power
  - start-up & shut-down costs
  - fuel costs
  - start-up & shut-down carbon emissions
  - start-up fuel consumption
  - start-up mode: cold, warm, hot
  - start-up time
  - min up & down times
  - ramp-up & ramp-down rates and costs
  - incremental costs
  - incremental carbon emissions
  - plant operating efficiency
  - variable operation & maintenance (O&M) costs
  - load factors of renewable technologies

- **<u>energy storage</u>**
  - power capacity (ramp up & down rates)
  - energy capacity

Technology selection and operation parameters for challenging biomass plants based on:

- Review on biomass and waste fuels previous experience and future opportunities in the UK
- Qualitative assessment and comparison of combustion technologies for biomass and challenging fuels based on performance criteria
- Identification of policy incentives and support mechanisms for power and CHP plants

- **<u>load shedding (pseudo generator)</u>**

Unit Commitment and Economic Dispatch (UCED) Model

UCED is a mathematical model that optimises the operation of a power system with minimum system cost over a specified period

<u>Inputs</u> to the model

Operational **characteristics of generators**	**Power *system* characteristics**	**<u>Model</u> set up**

- ➢ electricity demand (either weather-corrected and scaled current demand or forecast demand)
- ➢ system inertia level and min load level
- ➢ largest loss of credible generation
- ➢ Solar and wind demand forecast uncertainty quantification
- ➢ system spinning reserve requirement
- ➢ carbon cost
- ➢ policy support mechanisms for specific generators

Unit Commitment and Economic Dispatch (UCED) Model

UCED is a mathematical model that optimises the operation of a power system with minimum system cost over a specified period

Inputs to the model

Operational characteristics of generators	Power *system* characteristics	**Model** set up

- decomposition method (day-by-day, continuous, rolling horizon etc.)
- model horizon (years, days, hours etc.)
- dispatch method (quick linear; piece-wise quadratic approximation of fuel function etc.)
- solution algorithm (mixed integer programming (MIP), priority-based dynamic programming (DP) etc.)
- algorithm execution time (seconds)
- relative optimality gap (for MIP solvers)

Unit Commitment and Economic Dispatch (UCED) Model

Outputs from the model

- minimised system costs
- power output of each plant at each interval
- net output of CCS plants at each interval
- storage power input at each interval
- power plant revenues & costs
- spinning reserve contribution of each plant at each interval
- status of each plant (*on* or *off*) at each interval
- hours plants have been online or offline
- penetration of renewable generators
- curtailment of renewable energy
- fuel-price uncertainty analysis
- electricity price at each interval
  - marginal price for meeting demand
  - marginal price for meeting demand and spinning reserve
- marginal price of extra capacity and turndown of each generator at each interval
- marginal price of ramp up & ramp down
- available reserve in the system at each interval
- carbon intensity levels (hourly without start-up & shut-down costs; average over the horizon with and without start-up & shut-down costs)

Unit Commitment and Economic Dispatch (UCED) Model

GB Electricity System

Plausible GB system including
- 30 GW wind
- 20 GW solar

Biomass Power Plant Options

- Co-firing Pulverised Fuel
- Dedicated Pulverised Biomass
- Circulating Fluidised Bed
- Bubbling Fluidised Bed
- Packed Bed – Grater

UCED (Unit Commitment Economic Dispatch) with challenging biomass

Opportunities in GB

- Preliminary results suggest PB boilers have the best performance
- Challenging fuels unlikely to play a significant role in UK electricity mix unless there is appropriate support

Regulations, Policy incentives & support mechanisms

Options being explored include
- Capacity Market
- 'Traditional' financial support (e.g. ROCs, Feed-in-Tariff)
- Additional measures to support investment

UCED model will be used to support

- Sensitivity analyses, with particular focus on fuel price and power-plant average efficiency
- Assessment of a variety of support mechanisms for challenging biomass plants

Conclusions

- **Fluidised bed and grate boilers** are the most widely used technologies for challenging fuels in power plants and CHP plants, with a power output within a range between 25 - 300 MW_e.

- **Waste wood represents up to 35% of the solid biomass** burnt in the UK for power generation. More than 16 power plants (> 20 MW_e) use challenging fuels, e.g. waste wood either alone or in combination with white wood.

- Preliminary results suggest PB/**grater boilers have the best performance**. Yet challenging fuels are unlikely to play a significant role in UK electricity mix unless appropriate support mechanisms are in place.

- **UCED model** using robust technical and economic parameters **will be used to support**
  - ✓ Sensitivity analyses, with particular focus on fuel price and power-plant average efficiency
  - ✓ Assessment of a variety of support mechanisms for challenging biomass plants

References

[1] European Commission (2012) 'Roadmap 2050', Policy, (April), pp. 1–9. doi: 10.2833/10759
[2] International Energy Agency (2013) Technology roadmap - Carbon capture and Storage, Technology Roadmap Carbon Capture and Storage. doi: 10.1007/SpringerReference_7300
[3] Karampinis E, Kourkoumpas D-S, Grammelis P, Kakaras E. New power production options for biomass and cogeneration. WIREs Energy Env 2015;4:471–85. doi:10.1002/wene.163.
[4] Agbor E, Zhang X, Kumar A. A review of biomass co-firing in North America. Renew Sustain Energy Rev 2014;40:930–43. doi:10.1016/J.RSER.2014.07.195
[5] Lüschen A, Madlener R. Economic viability of biomass cofiring in new hard-coal power plants in Germany. Biomass and Bioenergy 2013;57:33–47. doi:10.1016/J.BIOMBIOE.2012.11.017.
[6] Basu P, Butler J, Leon MA. Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants. Renew Energy 2011;36:282–8. doi:10.1016/J.RENENE.2010.06.039
[7] Amirabedin E, Mcilveen-Wright. A Feasibility Study of Co-Firing Biomass in the Thermal Power Plant at Soma in order to Reduce Emissions: an Exergy Approach. Int J Environ Res 2013;7:139–54.
[8] Caillat S, Vakkilainen E. Large-scale biomass combustion plants: an overview. Biomass Combust. Sci. Technol. Eng., Elsevier; 2013, p. 189–224. doi:10.1533/9780857097439.3.189.
[9] Gonzalez-Salazar MA, Kirsten T, Prchlik L. Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables. Renew Sustain Energy Rev 2018;82:1497–513. doi:10.1016/j.rser.2017.05.278.
[10] IRENA. Renewable Energy Cost Analysis: Biomass for Power Generation. vol. 1. Abu Dhabi: 2012.
[11] Schröder A, Kunz F, Meiss J, Mendelevitch R, von Hirschhausen C. Current and Prospective Costs of Electricity Generation until 2050 2013. Berlin: 2013.
[12] Mott MacDonald. UK Electricity Generation Costs Update. Brighton: 2010. doi:www.mottmac.com.
[13] Office of Gas and Energy Markets. Renewables Obligation Annual Report 2016-17. London: 2018.

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