



Technical properties of biomass and solid recovered fuel (SRF) co-fired with coal: Impact on multi-dimensional resource recovery value



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ABSTRACT

The power plant sector is adopting the co-firing of biomass and solid recovered fuel (SRF) with coal in an effort to reduce its environmental impact and costs. Whereas this intervention contributes to reducing carbon emissions and those of other pollutants related with the burning of fossil fuel, it may also result in hidden impacts that are often overlooked. When co-firing, the physical and chemical properties of the mixed fuels and the subsequent technical implications on the process performance and by-products are significant. Interconnections between multiple values nested within four domains of value, i.e. environmental, economic, technical and social, mean that changes in the one domain (in the co-firing case, the technical one) can have considerable implications in the other domains as well. In this study, using a systematic and flexible approach to conceptualising multi-dimensional aspects associated with the co-firing of biomass and SRF with coal, we unveil examples of such interconnections and implications on overall value delivered through the use and recovery of waste resources. Such an analysis could underpin the selection of useful metrics (quantitative or semi-quantitative descriptors) for enabling a systemic multi-dimensional value assessment, and value's distribution amongst interconnected parts of resource recovery systems; key in enabling sound analysis and decision-making.

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1. Introduction

Combustion of coal for electricity production is one of the most significant sources of air pollution worldwide. This is owing to emissions of particulate matter (PM₁₀ and PM_{2.5}), carbon dioxide (CO₂), oxides of sulphur (SO_x) and nitrogen (NO_x) and acid gases (e.g. HCl, HF) (Sami et al., 2001), which lead to negative impacts on human health and ecosystems. The need to control and reduce carbon emissions and air pollutants has driven various interventions, most of them focusing on lowering fossil fuels dependence through the use of alternative sources of energy (Buchanan et al., 2014; Sami et al., 2001).

Biomass, which can be sourced from forestry and agricultural residues, or from dedicated energy crops (IEA-ETSAP and IRENA Technology, 2013), has long been used in power plants as a renewable fuel contributing to global energy production. Solid recovered fuel (SRF), a highly heterogeneous mixture of high calorific fractions of non-hazardous waste materials produced based on EU specifications (European Committee for Standardization, 2011), has been recognised as a viable alternative to fossil fuels, already

used as a co-firing fuel in various industrial sectors, including power plants (Agraniotis et al., 2009; Cocchi et al., 2015; Dunnu et al., 2009a; Gehrmann et al., 2012; Hilber et al., 2007b; Velis and Cooper, 2013; Wu et al., 2009).

Co-firing coal with biomass and/or SRF has increasingly been considered as a way to decrease reliance on coal and its associated impacts (Cocchi et al., 2015; Nussbaumer, 2003b; Velis et al., 2012; Wu et al., 2009). Co-firing can be achieved via three main options: direct co-firing; parallel co-firing; and indirect co-firing (Al-Mansour and Zuwala, 2010; Basu et al., 2011; Dai et al., 2008; Maciejewska et al., 2006; Tillman, 2000). The technologies used for indirect and parallel co-firing are not mainstream owing to their high investment costs. Conversely, direct co-firing offers savings in installation time, fewer modifications, shorter shutdown periods, and lower investment costs (Grammelis et al., 2010; Nussbaumer, 2003a), making it the co-firing method considered in this study.

The potential environmental benefits of using SRF and/or biomass as a fuel in power plants are improved carbon emissions (related to the carbon neutral attribution to their biogenic carbon fraction) (Séverin et al., 2010), and reduction in other types of air pollutants owing to their low nitrogen and sulphur contents (Cocchi et al., 2015; Sami et al., 2001; Velis et al., 2010; Wu

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et al., 2009). The costs of sourcing and processing (transportation, grinding, etc.) biomass and SRF may be lower compared to the costs associated with coal, making these fuels more affordable in some cases (Sami et al., 2001; Wu et al., 2009). They may also attract subsidies for production of renewable and/or carbon neutral energy, which depends on the exact policy mixture applicable in each country.

However, the decision to partially replace coal with either biomass or SRF also has technical implications. These implications result from the biomass and SRF characteristics and their synergistic effects with coal, of which real impact on wider systems is not yet fully clear, altering the balance between the environmental, economic, and social benefits (positive changes in value) and impacts (negative changes in value). For example, the relatively high sodium (Na), potassium (K), and chlorine (Cl) contents of biomass and SRF compared to coal, may lead to increased ash deposition on the boilers (Cocchi et al., 2015; Jappe Frandsen, 2005); the economic impact of which may depend on the technology used, as well as on the types and proportion of biomass and SRF co-fired with coal (level of substitution of coal). Another drawback of co-firing SRF and biomass with coal is that their relatively higher Cl content (e.g. for SRF it can be around 1% wt. (Velis et al., 2010)) may compromise the quality of the pulverised fly ash (PFA), thereby affecting its end uses (Wu et al., 2009). PFA is widely used as a technical addition partially replacing cement in concrete, improving its structural properties and reducing its carbon emissions (Imbabi et al., 2012; Purnell and Black, 2012). Changes in the quality of PFA can render it unsuitable for use in concrete production, thus limiting its recovery as a valuable resource (Baxter, 2005) and impacting an economically, socially and environmentally significant system dependent on the power generation sector.

Therefore, this study aims to describe how the physical and functional properties of biomass and SRF may affect the direct co-firing process and to assist in understanding of how these technical implications can result in environmental, economic and social benefits and impacts. This analysis is based on a systematic and flexible approach to conceptualising multi-dimensional aspects associated with the co-firing of biomass/SRF with coal; useful in providing insights into how to best capture the highest value of input and output materials from the co-firing system, thereby supporting the recovery of resources from waste. As such, in Section 2 the physical and technical characteristics of SRF and biomass are outlined as the basis of the exploration of the potential implications that these physico-chemical characteristics can bear on the co-firing system. Then in Section 3, the varying technical quality of biomass and SRF are explored in terms of their potential to directly affect the creation and or dissipation of technical. The systemic environmental, economic, and social valuation of co-firing SRF and/or biomass with coal is then discussed in Section 4, unravelling the potential opportunities and constraints associated with co-firing.

2. Physical and technical characteristics of biomass and SRF

2.1. Biomass properties and uses

Biomass is a material with a composition of approximately 80% volatile matter and 20% fixed carbon (as a measure of comparison, bituminous coal has 70–80% fixed carbon and 20–30% volatile matter) (Tumuluru et al., 2011). This composition renders biomass suitable as a fuel (Maciejewska et al., 2006). It can be imported or supplied locally, and may include residues or waste streams from forestry and timber processing (e.g. saw dust, wood chips, etc.), agriculture (e.g. corn husks, wheat chaff, etc.), pulp and paper, and sugar industries, as well as husk/shell wastes (e.g. almond,

olive, walnut, palm pit, cacao). In addition dedicated energy crops, including short-rotation woody crops like hard wood trees and herbaceous crops like switchgrass, are agricultural crops that can be grown solely for use as biomass fuels (Demirbas, 2004; Maciejewska et al., 2006; Sami et al., 2001). Oil, sugar and starch crops are currently widely used for the production of liquid transport fuels, and their utilisation in power plants is currently economically unjustified (Demirbas, 2004; Maciejewska et al., 2006).

Biomass is generally high in moisture content (MC) and has a low net calorific value (NCV) (Nunes et al., 2014). Its NCV is generally slightly over half that of coal, its particle densities are about half that of coal, and its bulk densities are about one fifth that of coal. This results in an overall fuel energy density roughly one tenth that of coal, meaning that more biomass has to be burnt to compensate for the energy equivalent of the coal that it replaced (Al-Mansour and Zuwala, 2010; Backreedy et al., 2005; Baxter, 2005; Demirbas, 2004; Nunes et al., 2014; Tumuluru et al., 2011). Biomass can also be processed into liquid, solid and gaseous fuels in order to transform often bulky, difficult to handle, and relatively low energy content material into one with the physico-chemical characteristics of traditional fuels, which permit economic storage and transferability through pumping systems (Demirbas, 2004; Maciejewska et al., 2006).

Chemical properties such as the Cl, nitrogen (N), Na, K, calcium (Ca) and sulphur (S) content vary widely amongst different types of biomass fuels (Demirbas, 2004; Maciejewska et al., 2006; Sami et al., 2001). Generally, wood and woody materials tend to be low in Cl, N, and ash content, while agricultural materials such as straw tend to contain high amounts of alkali metals (mainly K) and Cl (Kassman et al., 2013; Teixeira et al., 2012). Biomass fuels may also have a varying ash content (i.e. the inorganic and incombustible mineral fraction of biomass fuels that is left after complete combustion) with agricultural materials presenting a higher ash content than woody materials (Demirbas, 2004; Nunes et al., 2014). However, biomass fuels have generally less ash, and very low or almost negligible N and S content compared to most coals (Sami et al., 2001; Tumuluru et al., 2011), reducing as such the fuel-related SO₂ and NO_x emissions responsible for acidification and ozone pollution, respectively (Easterly and Burnham, 1996). Due to the large property variations presented by the different types of biomass, it is difficult to establish a representative biomass classification. However, some typical biomass fuel properties are presented in Table 1, and are compared to those of bituminous coal (i.e. coal with 70–80% fixed carbon and 20–30% volatile matter).

Stand-alone biomass plants purport to convey environmental and economic benefits via e.g. the utilisation of a renewable fuel, the diversion of biodegradable material from landfill, and subsequent eligibility for tax credits and subsidies, but they involve a high capital cost and significant investment risk associated with the security of the feedstock supply, regulatory volatility (especially regarding the stability of subsidies) and thus the long-term viability of the plant (Maciejewska et al., 2006). Seasonality aspects may affect the availability of biomass fuel, while the dispersed nature of most biomass fuels produced in different regions and their lack of proximity to existing infrastructure can add further project risks (Maciejewska et al., 2006).

Combining biomass with other fuels (e.g. coal and SRF) for energy production in existing power plants can mitigate and address some of these technical, economic and environmental uncertainties. This is especially the case when biomass is sourced locally, making co-firing more economically attractive (Basu et al., 2011). If local sources are not sufficient, high energy-density, pre-treated biomass (e.g. wood pellets) can be used, in which case long-distance transportation logistics (e.g. availability of suitable infrastructure such as ports, rail, roads etc.) play an important role in both the economic viability and the overall environmental

Table 1

Properties of typical biomass fuels compared with coal, % dry weight (wt.d) unless otherwise indicated.

Property	Coal ⁱ	Wood materials ⁱⁱ	Bark ⁱⁱⁱ	Straw ^{iv}	Grass ^v
NCV (ar) (MJ/kg)	26–28	18.5–20	18.5–23	10.6–17.4	17.1–17.5
MC (% wet)	2.1–10	3–60	45–65	17–25	15–20
Ash content (% wt d)	6.2–10.9	0.4–3.14	2–7	5–6.6	2.25–7.5
Cl (% wt. d)	≤0.1 (exc.0.255 ¹)	0.01–0.03	0.01–0.03	0.14–0.97	0.09
K (% wt. d)	0.003–0.210	0.02–0.05	0.1–0.4	0.69–1.306	0.3–0.5
Ca (% wt. d)	0.13–12	0.1–1.5	0.02–0.08	0.1–0.6	9
C (% wt. d)	66.23–87	40.51–53	48–54.9	39.4–49	45.5–46.1
H (% wt. d)	3.5–5.94	4.82–6.78	5.7–6.8	5.0–6.97	5.7–6.86
O (% wt. d)	2.8–11.3	33.39–55.13	24.3–43.2	40–46	44
N (% wt. d)	0.8–1.5	0.08–0.12	0.3–0.8	0.4–0.8	0.65–1.04
S (% wt. d)	0.5–3.1	≤0.19 ⁱⁱ	≤0.1	0.05–0.2	0.08–0.18

ⁱ Ranges derived from bituminous coal properties reported in the studies of (Basu et al., 2011; Dai et al., 2008; Duong et al., 2010; Teixeira et al., 2012; Tumuluru et al., 2011; Wu et al., 2009; Wu et al., 2011, 2013).

ⁱⁱ Ranges derived from comparison of wood/wood material properties reported in different studies and include wood without bark (Tumuluru et al., 2011); fuelwood, sawdust, hardwood, softwood, redwood, tan oak (Sami et al., 2001); pine wood and oak wood (Grammelis et al., 2010); hardwood maple (Basu et al., 2011); average of 11 hardwoods and 9 softwoods (Ragland et al., 1991); wood waste (Duong et al., 2010); beech, spruce, and red oak wood (Demirbas, 2004); pinewood (Backreedy et al., 2005); unspecified wood (Dai et al., 2008).

ⁱⁱⁱ Ranges derived from comparison of wood barks properties reported in different studies and include unspecified bark (Tumuluru et al., 2011); beech wood bark (Demirbas, 2004); pine and oak bark (Ragland et al., 1991); unspecified bark (Dai et al., 2008).

^{iv} Ranges derived from comparison of straw properties reported in different studies and include unspecified straw fuel (Tumuluru et al., 2011); barley and wheat straw (Sami et al., 2001); wheat straw (Demirbas, 2004); straw pellets (Teixeira et al., 2012); unspecified straw (Dai et al., 2008).

^v Ranges derived from comparison of grass properties reported in different studies and include reed canary grass (Tumuluru et al., 2011); switchgrass (Sami et al., 2001); switchgrass (Demirbas, 2004); switchgrass (Duong et al., 2010).

¹ Cl content in polish coal as reported in (Teixeira et al., 2012).

impact. Although many different types of biomass can be co-fired with coal, the preparation, storage and handling of these biomass fuels and the type of co-firing processes used present varied technical challenges that can affect power plant efficiency and waste management (i.e. ash by-product use and/or disposal) (Backreedy et al., 2005; Maciejewska et al., 2006; Nunes et al., 2014; Teixeira et al., 2012).

The type of biomass chosen for a particular co-firing application depends on technical and economic factors such as pre-treatment, composition, heating value, density, porosity, size, active surface area, and ash sintering temperatures (Koppejan and Van Loo, 2012). The majority of biomass co-firing installations are operated at biomass to coal ratios of less than 10%, on an energy basis. The successful operation of these plants suggests that co-firing at such low ratios does not pose major problems to the boiler operation in most cases. Higher ratios require much closer attention to the particular co-firing option and technology available (Al-Mansour and Zuwala, 2010; Basu et al., 2011; Dai et al., 2008).

2.2. SRF properties and uses

SRF in Europe is strictly defined as according to the stipulations of the EN 15359 (European Committee for Standardization, 2011). It may be produced from the advanced processing of combustible fractions of non-hazardous materials recovered from municipal solid waste (MSW), commercial and industrial (C&I) waste and construction and demolition waste (CDW), such as paper, cardboard, wood, textiles and plastics (Di Lonardo et al., 2016; Garg et al., 2007; Maier et al., 2011; Wu et al., 2011). Processing takes place in mechanical-only or mechanical-biological treatment (MBT) plants. SRF is therefore a quality assured fuel, and should not be confused with the term 'refuse-derived fuel' (RDF). RDF despite being initially (1980s) quality assured in the US, has resulted to currently denoting a non-standardised low quality fuel that typically contains mixed unprocessed combustible components of MSW. These days RDF is often traded (exported) within Europe to feed only into energy from waste (EfW) plants. More detailed terminology clarifications are provided elsewhere (Velis et al., 2010).

SRF is usually produced and traded in the form of bales, fluff, and soft/hard pellets (Hilber et al., 2007a). Based on data from the European Recovered Fuel Organisation (ERFO), the potential aggregate SRF production from MSW, C&I waste and CDW in the EU is around 60 Mt per year (Cuperus, 2017), and this could potentially be used in power generation plants (~16 Mt/year), cement industry (~12 Mt/year), other industries (~12 Mt/year), biomass power generation (~6 Mt/year), and district heating (~2 Mt/year). In the UK, due to the inconsistent use of the terms and descriptions of RDF/SRF and the lack of tracking and reporting of its production and use across UK and Europe, there is not robust evidence in regards to SRF's production and use. Nevertheless, based on export data on RDF/SRF and data on the proportion of SRF in the total RDF/SRF quantity exported, it was extrapolated that SRF exported from the UK in 2012 was around 99.7 kt (AMEC Environment & Infrastructure UK Limited, 2013).

Depending on its composition, SRF can typically be characterised by an energy content in the range of 10–25 MJ kg⁻¹ ar (ar: as received), which make it attractive as a co-fuel for many industrial processes, improving ignition, combustion stability and burn out of lower-grade fuels such as biomass, peat or low-rank coals (Frankenhaeuser et al., 2008; Montané et al., 2013; Wu et al., 2011). With a typical biogenic content around 50–65% on energy basis, SRF is attractive as alternative fuel, being partially renewable and carbon-neutral, and therefore qualifying for subsidies such as renewable obligation certificates (ROCs) in the UK and emissions trading schemes (e.g. the European emission trading scheme EU-ETS).

Even within a circular system, where the physical and technical properties of materials, components and products (MCPs) are retained in the economy for longer, at their highest possible value, the production and use of SRF can be genuinely complementary to materials recycling. This is particularly the case where the technical value represented by the calorific or biogenic content of materials apparently outweighs other technical, environmental and economic values associated with their recoverability (e.g. materials that cannot be sustainably or even practically recycled because of poor quality). This is recognised in the recent EU waste-to-energy strategy, where increased use of SRF is advocated as being part of making the transition to a circular economy given that the

EU waste hierarchy is used as a guiding principle and that choices made do not prevent higher levels of prevention, reuse and recycling, while contributing to decarbonisation, in line with the Energy Union Strategy and the Paris agreement (European Commission, 2017). This makes its production and use potentially an integral part of solid waste resource recovery systems, especially where there is need/opportunity to serve as replacement fuel in existing and entirely fossil (coal- or heavy oil-) fuelled plants.

In Europe, SRF production according to the European Committee for Standardization must follow a series of clearly defined standards developed by CEN/TC 343, and especially the generic standard EN 15359 (Maier et al., 2011). The EN 15359 defines the detailed quality specifications needed for SRF, and provides a fast track system (classification) for characterizing the SRF based on combinations of three key properties, designed to secure fuel quality, while minimising classification complexity (Garg et al., 2007). The key technical classification properties are: (i) the NCV (also known as lower heating value), (ii) the total Cl content, and (iii) the mercury (Hg) content; these serve, respectively, as indicators for the economic, technical and environmental performance associated with SRF use (Table 2) (European Committee for Standardization, 2011).

Briefly, the NCV describes the amount of heat or energy generated when SRF is completely combusted; the Cl content is a measure of the potential corrosion, slagging and fouling effects in boilers, whereas the Hg content (one of the most significant global environmental pollutants because of its medium and long term impacts on health) (Rice et al., 2014) is a measure of the potential toxicity released in the environment as its high volatility makes it the most challenging to capture in the air pollution control systems treating the flue gas after combustion.

Each property of SRF is thus distinguished into five classes; Class 1 exhibits the most desirable attributes of SRF and quality declines with increasing class number (Del Zotto et al., 2015; Di Lonardo et al., 2016; Garg et al., 2007). The combination of the class number of each property forms the class code of SRF; there are thus, theoretically, 125 SRF class codes combinations (Del Zotto et al., 2015; Di Lonardo et al., 2016). For example, a fuel having a NCV of 23 MJ kg⁻¹, mean Cl content of 0.9% and Hg content of 0.025 mg MJ⁻¹ (median) and 0.05 mg MJ⁻¹ (80th percentile) would have the class code: NCV-2; Cl-3; Hg-2. In the case of Hg the worst case of the two statistical values (i.e. the median and the 80th percentile) takes precedence when determining the class of Hg content; hence, in this example the 80th percentile was used. The quality rating of SRF as a co-fuel in coal power plants is generally restricted to classes 1 and 2 of each of the three classification parameters (Dunnu et al., 2009b; Garg et al., 2009; Velis et al., 2010).

The classification of the SRF produced is determined by the area-specific MSW, C&I and CDW management strategies (e.g. source segregation of recyclables, source-segregation of food waste, etc.), the resultant composition of these waste streams, as well as the processing capabilities of the plants that treat MSW, C&I and CDW. The growth of the recycling markets available (Di Lonardo et al., 2016; Garg et al., 2009; Rada and Ragazzi, 2014) constitute also an integral part of this system.

The quality of SRF can be improved by concentrating only suitable combustible fractions (such as plastics, packaging composites, textiles, etc.) (Velis et al., 2010) (Nasrullah et al., 2015a, b) and removing physical (glass, stones, ferrous and non-ferrous metals) contaminants. Materials with high Cl and lead (Pb) content are undesirable (Eckardt and Albers, 2003) and their removal is seen as a priority. Rada and Ragazzi (2014) report that efficient separate collection of materials made of polyvinylchloride (PVC: pipes, sheets, panels, tiles, toys, paints) and of others that contain chloride such as bleached paper and industrial solvents (e.g. degreasers, cleaning solutions, paint thinners, pesticides, resins and glues) could reduce the Cl content. Separate collection of waste electrical and electronic equipment (WEEE), thermometers, batteries, paints and electroplated metals can reduce the Hg and cadmium (Cd) contents in the residual MSW and C&I and CDW waste streams, thereby improving the relevant SRF class (Rada and Ragazzi, 2014).

Yet, there is a trade-off between biogenic content and fossil polymers content, the latter of which boosts the calorific value. In a number of studies it has been reported that plastics, and particularly PVC, often contribute the highest Cl content of the waste (ca. 70% of the Cl in MSW) (Vainikka et al., 2011a), but also provide a large proportion of the CV of the fuel (Ma and Rotter, 2008; Nasrullah et al., 2015c; Rotter et al., 2004; Vainikka et al., 2011a). Near-infrared (NIR) technologies used in MBT plants could potentially remove plastics with high Cl content, such as PVC (Nasrullah et al., 2015b). However, the presence of black plastics, untreated wood, and textiles may hamper the efficiency of NIR technology to successfully sort PVC plastic, leaving an important fraction of it in the SRF produced; hence, increasing its Cl content (Zeiger, 2006).

In particular, PVC is commonly recognised in the waste industry as being a concentrated source of organically-bound chloride that can be problematic in thermal treatment processes owing to the production of HCl during combustion (Deans et al., 2016). However, a substantial quantity of chloride can be also found in household kitchen and yard waste (bio waste) in the form of inorganic alkali metal chlorides, e.g. NaCl, MgCl₂, KCl and CaCl₂ (Ma and Rotter, 2008). Whilst the concentration of chloride in these waste streams is lower than that found in PVC, the overall composition of the waste may mean that inorganic chloride could potentially contribute more to the overall chloride load – i.e. there may be more biological waste than PVC in a mixed waste stream (Deans et al., 2016).

Properties other than the NCV, Cl and Hg content, such as moisture content (MC), volatiles fraction, particle size, ash content, heavy metals, etc., are also important for the practical assessment of SRF's behaviour in combustion plants (Di Lonardo et al., 2016; Garg et al., 2007; Velis et al., 2010; Wrap, 2012). The processes employed in MBT plants (i.e. the biodrying process followed by mechanical separation, or the extensive mechanical separation process) may affect the MC and hence the NCV of the SRF produced. Biodegradable waste, and specifically food waste that is often present in the MSW, can increase the MC of the SRF. When the food waste content in MSW is around 50% or more, then the

Table 2
SRF classification based on its three key parameters (European Committee for Standardization, 2011).

Indicator	Property	Units (Statistical measure)	Classes				
			1	2	3	4	5
Economic	Net calorific value (as received, ar)	MJ kg ⁻¹ (mean)	≥25	≥20	≥15	≥10	≥3
Technical	Chlorine content (dry)	% wt wt ⁻¹ (mean)	≤0.2	≤0.6	≤1.0	≤1.5	≤3.0
Environmental	Mercury (ar)	Mg MJ ⁻¹ (median)	≤0.02	≤0.03	≤0.08	≤0.15	≤0.50
		mg MJ ⁻¹ (80th percentile)	≤0.04	≤0.06	≤0.16	≤0.30	≤1.00

biodrying process followed by mechanical separation is considered to be most advantageous for SRF production as it can reduce the MC to around 15% wt. d (Rada and Andreottola, 2012; Velis et al., 2010).

In regard to particle size classification, screening used in MBT plants sorts waste particles mainly according to their size (Velis et al. 2010). Particle size may be further adjusted by further comminution of the waste (secondary shredding). Power plants operate best using SRF with a particle size of 20 mm (median value), whereas cement plants can tolerate up to 30 mm (Garg et al., 2007). Based on quality specifications SRF can have a particle size in the range of 5 mm to <300 mm, with the highest particle size applications being utility boilers (i.e. <10–200 mm in fluidised bed, <300 mm in grate firing) and hot disc cement kilns (HDF) at <120 mm (Lorber et al., 2012).

All of the above will eventually determine the proportion of SRF that can be co-fired with coal in power plants and whether it can be successfully used as a 'low-carbon' fuel. The ratio of SRF to coal must be carefully controlled, as it alters the behaviour of combustion, in turn affecting the type and scale of the technical implications that may arise due to the synergistic effects of SRF and coal (Wu et al., 2009).

3. Conceptual assessment of the multi-dimensional value implications of direct co-firing of biomass and SRF with coal

Whilst it is widely accepted that direct co-firing of biomass and SRF with coal can be an attractive strategy for reducing at-source CO₂ emissions, the co-combustion process is not as straightforward as it may appear. The percentage of coal, biomass and SRF in the fuel blend, the type of biomass and SRF used, the fuel preparation, storage, and handling practices, and the suite of technologies available for the co-firing process on the one hand, and the differing fuel characteristics and synergistic effect of the compounds released therefrom on the other, can lead to a number of technical implications associated with ash deposition, pollutant formation, corrosion in the processing equipment, and use of PFA (Baxter, 2005; Dai et al., 2008; Grammelis et al., 2010; Wu et al., 2013). The potential use of the PFA as a technical additive in the manufacture of high-quality, low carbon concrete – an important recycling route for this otherwise wasted by-product – can be severely compromised (Maciejewska et al., 2006). This is clearly a hindering factor from the perspective of resource recovery from waste, but a thorough assessment of how such technical constraints can have implications in the environmental, economic and social domains of value of the wider system with which the power generation system interacts, is required to be able to assess overall whether this is a positive or negative trade-off.

Gaining an insight into how the co-firing process influences the interdependencies between technical and environmental, economic and social aspects, regardless of the technologies used, is of major importance in perceiving overall value creation, distribution and dissipation in the wider system. Table 3 presents these implications and interdependencies against biomass and SRF properties, when these fuels are co-fired with coal.

In direct co-firing, SRF and/or biomass may be combined with coal in the combustion system in three ways: using (i) the same mill (i.e. fuel pulverising equipment) and burner (i.e. mechanical equipment that burns pulverised fuel); or (ii) separate mills and same burner, or (iii) separate mills and burners, depending on SRF/biomass characteristics (Al-Mansour and Zuwala, 2010; Basu et al., 2011; Dai et al., 2008; Maciejewska et al., 2006). The configuration and technologies used can profoundly affect the performance of the co-firing process owing to differences in the MC the particle size distribution and their dispersal characteristics during

the feeding process when fuels are injected into the furnace, but this is beyond the scope of this study.

3.1. Impact of moisture content (MC)

Blending biomass and SRF with coal in existing coal processing equipment (e.g. coal mills, crushers, pulverisers), using the same or separate mill but same burner may result in a number of shortcomings due to dissimilarities in their MC. Biomass and SRF have a higher MC than coal, which may vary significantly based on the source and variations in the recovery, storage and drying conditions and processing (Demirbas, 2004; Easterly and Burnham, 1996; Nunes et al., 2014; Tumuluru et al., 2011). A high MC may result in ignition problems and reduction of the maximum combustion temperature (Lu et al., 2008). This can hamper the burn out of the biomass and SRF fuels and result in CO emissions, creation of soot (unburned fine carbonaceous material) and the formation and emissions of Polycyclic Aromatic Hydrocarbons (PAH), all of which are associated with high environmental and social 'costs' (Dai et al., 2008; Nussbaumer, 2003a; Wu et al., 2011).

Soot is around 2.5 µm or smaller in diameter, and is chiefly composed of carbon and small amounts of acids, chemicals, metals, soils, and dust. It can react with sunlight to form haze, which affects visibility and causes pollution; or it may be combined with moisture in the atmosphere to form acid rain, leading to degradation of water quality, nutrients depletion in the soil and damage of sensitive crops, and change of the nutrient balance in various ecosystems. Soot inhalation by humans and its penetration deep into the lungs has been linked to a wide range of serious health impacts, including premature death, heart attacks, and strokes, as well as acute bronchitis and many other respiratory illnesses (Keefe, 2013; Lighty et al., 2000). Soot can also be a carrier of organic compounds such as PAHs.

PAHs are emitted to the atmosphere primarily from the incomplete combustion of organic matter. PAHs intake into the body via respiratory, dermal, and gastrointestinal routes can cause premature death, chronic asthma, and respiratory problems, while exposure to them for long periods can lead to the development of cancer (Abdel-Shafy and Mansour, 2016; Kim et al., 2013).

The form in which the biomass and SRF fuels are injected into the boiler (e.g. as powder, fluff, cubes, pellets, briquettes or granules) will affect the time required for them to be heated-up and combusted relative to the coal, potentially increasing their residence time in the boiler and thus the operational and maintenance costs. By contrast, a process in which separate mills and burners are used can ensure that a complete burn-out of the fuels is achieved, fully exploiting their energy content and reducing environmental and human health impacts.

3.2. Impact of bulk density and particle size

Another technical factor that can cause the slow burn out of the biomass and SRF fuels is an unsuitable particle size distribution (PSD) (Del Zotto et al., 2015; Dunnu et al., 2009b). According to Wu et al. (2011) the d₅₀ (denoting 50 vol.% of the particles are below this size) of SRF was approximately 164 µm, two orders of magnitude higher than that of coal (d₅₀ of the coal particles was about 19 µm). This difference in the particle size distribution can result in SRF particles falling through the furnace without their complete burn out (Del Zotto et al., 2015). Similarly, the blending of biomass with coal can result in similar shortcomings. Blending and burning of straw with coal, for example, is not possible owing to segregation of the two materials driven by their differing densities and particle shapes (Dai et al., 2008). However, not all biomass suffers this; sawdust has a favourable particle size distribution and can be directly blended and burnt with coal (Maciejewska et al.,

Table 3
Biomass and SRF properties and their effects on co-firing with coal in power plants.

Biomass/SRF properties	Technical effects	Implications		
		Environmental	Economic	Health & Social
Moisture content	Lowers the NCV ^{1,2} Can cause ignition and incomplete combustion problems ^{3,4} Leads to emissions of unburnt pollutants such as CO, soot, and PAH ^{1–5}	Soot can cause environmental degradation due to formation of haze and acid rain ²⁰ PAHs are highly toxic, mutagenic and/or carcinogenic to microorganisms ²⁰	Higher investment costs due to boiler retrofitting to deal with combustion problems ^{1,5} Higher investment costs for separate mills and burners for dealing with incomplete combustion ¹	Fine particles can cause severe health impacts PAHs have toxic, mutagenic and/or carcinogenic properties when absorbed or inhaled by humans ²⁰
Bulk density	Feeding problems (e.g. bridging and stoppage) ¹		Additional investment cost for storage, transport, handling and separate feeding ^{1,3,5}	
Particle size (usually bigger than of coal's)	Lowers the ignition temperature ^{1,6} Reduces carbon burnout leading to increased CO production ^{2,7} Reduces stability of fuel injection due to agglomeration of SRF particles ^{2,7}	Increased CO ₂ emissions due to lower fuel injection stability and reduction in the burnout ⁸	Higher costs for pre-treatment and particle size reduction ^{1,5} Higher utility costs ²	
Ash content	Ash utilisation problems due to high alkaline metal content (e.g. K and Na) ^{9–11}	Particulates emissions ¹	Additional costs for ash disposal ¹	Particulates can cause respiratory problems and bioaccumulation
Cl content	Induces the corrosion of heat transfer surfaces in the boiler ^{1,2,9,12,13} Lowers the quality of the fly ash ^{5,9,14} Decreases the electric efficiency of the boiler ⁵	Aerosol formation ¹ Land degradation from fly ash disposal	Higher operational and maintenance costs due to corrosion ^{1,5,10,15} Additional costs for fly ash disposal routes ¹	
Alkali and alkaline earth metals (e.g. K, Na, Ca, Mg)	Slagging and fouling of the boiler equipment ^{1,9–11,16,17} Corrosion of heat exchangers and superheaters ^{2,3,7,8,18} Poisoning of the SCR system for NO _x emissions reduction ^{3,5,7,8,13,18} Ca favours the formation of calcium sulphate retaining more sulphur in ash ^{1,2,13} Compromise the end use of fly ash ⁵	Aerosol formation ¹	Higher operational and maintenance costs due to increased fouling and corrosion, and poisoning of the SCR catalysts ⁵ Additional costs for fly ash disposal routes ¹	
Silica (Si) content	Favours the formation of ash and its deposition that causes erosion of the heat transfer tubes ^{9,11}		Higher operational and maintenance costs due to extended erosion ⁵	
Potentially toxic elements (PTEs) and fine particles	Increased potential for heavy metals to be trapped in ash ¹ Ash utilisation and disposal issues ¹ Increased formation of submicron particles (<0.2 µm) ^{13,19}	Emission of highly volatile elements such as Hg, Cd and Thallium (Tl) ⁹ Aerosol formation ^{1,20}		Potential harm to human health from fine particle respiration and irritation ^{13,19,20}

¹Dai et al., 2008; ²Wu et al., 2011; ³Baxter, 2005; ⁴Demirbas, 2004; ⁵Nussbaumer, 2003a; ⁶Lu et al., 2008; ⁷Wu et al., 2009; ⁸Wu et al., 2002; ⁹Del Zotto et al., 2015; ¹⁰Teixeira et al., 2012; ¹¹Easterly and Burnham, 1996; ¹²Hilber et al., 2007a; ¹³Wu et al., 2013; ¹⁴Maciejewska et al., 2006; ¹⁵Åmand and Kassman, 2013; ¹⁶Berda and Rog, 2013; ¹⁷Kassman et al., 2013; ¹⁸Jappe Frandsen, 2005; ¹⁹Frandsen et al., 2011; ²⁰Lighty et al., 2000.

2006). Both biomass and SRF particles can become agglomerated during their injection in the reactor, a phenomenon that increases their effective average size and reduces process efficiency (Wu et al., 2011, 2013).

Size reduction of biomass and SRF fuels to a PSD similar to that of coal is generally not economically feasible due to their low bulk density, the non-uniform particle size and shape and issues of selective shredding of items with too variable elasticity brittleness (e.g. wood vs. plastic film) (Dunnu et al., 2009b); however, some size reduction is generally required in order to avoid the risk of incomplete combustion and associated shortcomings (Dai et al., 2008; Del Zotto et al., 2015; Sami et al., 2001). When the size characteristics of the fuels do not vary too much, the same feeding system can be used. However, if the size distribution of the fuel particles varies widely then a separate feeding system for biomass and SRF is normally used, at the expense of high investment and operational and

maintenance costs, in order to attain comparable burning rates to those of coal (De and Assadi, 2009; Dai et al., 2008).

The need for a separate feeding system, in addition to the proportionally greater volumes of SRF and biomass that need to be shipped, transported, stored and handled (owing to their low bulk densities) for receiving the same energy content as that of coal, means that higher costs may have to be incurred (Table 3) (Basu et al., 2011; Baxter, 2005; De and Assadi, 2009; Del Zotto et al., 2015; Lam and Sokhansanj, 2014). This may present potential infrastructural problems, especially if existing logistic systems are not able to accommodate such changes, and new planning and investment would need to be sought. In addition, economic implications due to biomass and SRF availability are further affected by the scale and rate of the fuels supply, as well as the local market conditions (such as gate fee, cost of landfilling, incentives for GHG emissions reduction, etc.) (Garg et al., 2007).

3.3. Synergistic effects of ash content and alkali and alkali-earth metals

The co-firing effect of biomass and SRF with coal on flue gas and ash generation is largely dependent on the content of alkali and alkali-earth metals (e.g. K, Na, Ca), and the Cl, P, Al, and Si content in the fuels (Dai et al., 2008; Hansen et al., 1998; Teixeira et al., 2012). The alkali and alkali-earth elements in biomass and SRF are often in ionic or organic forms, which are more volatile than their mineral forms. As a consequence, these elements are more easily vaporised during co-firing, affecting the ash melting behaviour and potentially leading to increased ash deposition in the boiler (Berda and Rog, 2013; Kassman et al., 2013; Teixeira et al., 2012).

Ash deposition can be categorised into slagging and fouling. Slagging refers to the deposition of molten alkali metal ashes in the high-temperature refractory sections of the boilers where radiative heat transfer is dominant; whereas fouling occurs in the convective heat transfer zones of the boiler due to the accumulation of fused ash deposits (Dai et al., 2008; Del Zotto et al., 2015; Hansen et al., 1998; Teixeira et al., 2012).

Ash deposition may aggravate corrosion in the heat transfer tubes, reducing the combustion efficiency, leading to further technical and economic implications owing to deterioration of combustion and boiler components and subsequent increased costs of operation and maintenance required (Åmand and Kassman, 2013; Dai et al., 2008; Demirbas, 2004; Teixeira et al., 2012). The alkali and alkaline earth metals may also result in the poisoning of the vanadium-based catalysts used in the selective catalytic reduction (SCR) systems, used for NO_x reduction emissions, affecting as such their performance. This may result in environment all implications from the release of NO_x emissions, and on the loss of economic incentives procured from NO_x control strategies (Baxter, 2005; Jappe Frandsen, 2005; Wu et al., 2002; Wu et al., 2009; Wu et al., 2011, 2013). The technical implications related to the end use of PFA in concrete production, may result in additional economic implications due to the need to identify and implement alternative routes for its utilisation and/or disposal (Johnson et al., 2010; Zheng et al., 2007).

3.4. Synergistic effects of Cl, alkali and alkali-earth metals, sulphur and silica content

3.4.1. Effects on process equipment

The higher Cl content of SRF and biomass compared to that of coal may lead to harmful effects on the combustion system and the environment. The release of Cl contained within the fuels promotes the vaporisation of the organically bound alkalis in coal, biomass and SRF to form alkali chlorides (e.g. NaCl and KCl). Alkali chlorides may aggravate ash deposition on the heating surfaces, and induce hot corrosion of the structural elements of the combustion equipment, due to chlorides penetrating the chromium passive film and iron in steel allowing its corrosion to occur leaving a nickel rich skeleton (Berda and Rog, 2013; Dai et al., 2008; Kassman et al., 2013; Wu et al., 2002; Wu et al., 2009; Wu et al., 2011; Zheng et al., 2007). The higher the alkali metals:chlorine ratio in the fuels (i.e. (Na + K)/Cl > 1) the more pronounced this effect is (Wu et al., 2011). High temperature corrosion can also be attributed to zinc (Zn) and Pb chlorides, as well as to Zn/Pb bromides which exhibit similar physical and chemical properties to those of chlorine (Del Zotto et al., 2015; Vainikka et al., 2011b). Due to the very specific applications of bromine, its concentration in SRF can be assumed to be lower than Cl and even negligible in biomass, but if present, its fate can be expected to be similar to that of Cl (Vainikka et al., 2011b).

A proportion of alkali chlorides may also react with gaseous sulphur and aluminium silicate compounds. Reactions of alkali chlorides with aluminium silicate compounds can form potassium-aluminium-silicates, which owing to their high melting temperature may lead to a reduction in ash deposition in the boiler and its corrosive effect (Zheng et al., 2007). The reaction product of alkali chlorides with gaseous sulphur are alkali sulphates (e.g. K₂SO₄) that may result in a less corrosive effect on the boiler; hence limiting the effects of KCl on the heat transfer surfaces (Berda and Rog, 2013; Wu et al., 2011, 2013). If sulphur is not present at sufficient amounts, ammonium sulphate may be injected into the flue gas after combustion to aid the conversion of gaseous potassium chloride into potassium sulphate, resulting in reductions in corrosion and deposition rates by 50%. Another option with similar results, is the pre-treatment of biomass by washing with water for which details are provided elsewhere (Maciejewska et al., 2006). Both the use of additives and the biomass pre-treatment option can be associated with additional costs.

A counter effect of the reaction of alkali chlorides with sulphur and aluminosilicates, is the release of HCl. HCl may increase sulphur retention in slag and fly ash through the formation of sulphate and alkali aluminium silicate (Dai et al., 2008; Wu et al., 2011), or it may form H₂SO₄ when released into the flue gas (Ma and Rotter, 2008). H₂SO₄ is a highly corrosive agent that condenses on the surface of ash particles (Dai et al., 2008; Wu et al., 2011). As such, its production is of particular concern because as reported by Lighty et al. (2000) H₂SO₄ has been shown to heighten respiratory impairment when ash particles are dispersed into the atmosphere (Lighty et al., 2000).

Additionally, the HCl may also react with CaO, leading to the formation and increase of alkali chlorides in the fly ash, retaining thereby an increased amount of Cl. Sulphur retention in the fly ash may also be promoted by the presence of increased amounts of Ca found in woody materials with high Ca content (Table 2) and SRF, which favours the production of calcium sulphates (Wu et al., 2011). It was reported that Ca to S ratios >3 can ensure effective sulphur retention via this reaction (Dai et al., 2008; Del Zotto et al., 2015).

3.4.2. Effects on pulverised fly ash (PFA)

High Cl content could adversely influence the PFA and bottom ash composition and quality, affecting their end use and thus their marketability. Especially with regards to PFA, the Cl content is considered to be a limiting factor for its end-use. Based on the revised statutory European standards (i.e. EN 450-1:2012 for the use of fly ash in concrete), Cl content in the PFA has to be ≤0.10 in order to be used in concrete production (Caldas-Vieira et al., 2013; Johnson et al., 2010). A higher Cl content in the PFA resulting from co-firing will have both economic and environmental implications from a resource management perspective. These implications relate to PFA disposal to landfill and associated economic costs, the loss of a “carbon neutral” and technically beneficial resource in the concrete industry, and the associated need for increased consumption of cement at a higher environmental and economic cost.

The amount of PFA produced and its properties, other than the Cl-content, depend on the type of biomass and SRF co-fired with coal (Grammelis et al., 2006a; Grammelis et al., 2006b). Coal co-fired with wood and woody materials that have a very low ash content, will generate less PFA than coal co-fired with agricultural residues that have a high ash content. Increased production of fly ash, especially if the concrete-based by-product route is compromised, may limit the environmental benefits of co-combustion, because of the increased land requirements for long-term storage of PFA and the high risk of groundwater contamination through heavy metals leaching (Johnson et al., 2010). Various standards

(e.g. EN 450-1:2012) specify permitted amounts and type of co-combustion material, combustion process specifications and the species limits that have to be met, in order for the PFA produced to be fit for use in the concrete industry. For instance, the combustion process has to operate at high temperatures (i.e. 1300–1500 °C) in order to facilitate glass formation in the fly ash (Caldas-Vieira et al., 2013; Jones et al., 2006). Some types of combustion technologies (e.g. grate fire and fluidised bed combustion boilers) thus produce residues that may not meet the PFA quality standards for concrete specifications (Caldas-Vieira et al., 2013). The co-firing of coal with wood, straw, olive husks, green wood (e.g. not recycled wood), cultivated biomass, animal meal, SRF and paper sludge can generate a PFA that may be used as a cement admixture, as long as it has a loss on ignition (LOI) value of less than 5%wt, contains less than 5%wt. carbon and 5%wt. total alkali content (Caldas-Vieira et al., 2013; Johnson et al., 2010; Zheng et al., 2007).

The physical properties of PFA (e.g. PSD) may also vary according to combustion parameters such as temperature and fuel loading rate (Johnson et al., 2010). The PSD of PFA can affect the compressive strength development of the concrete in which it is used, with ashes more abundant in smaller particles contributing more to long term strength. In addition, it may also affect the emission control strategies and the toxicity of the resulting PM emissions, leading to both environmental and economic implications.

3.5. Impact of potentially toxic metals, metalloids and ultrafine particles

The fate of certain trace elements in biomass and SRF during co-firing has not been fully established. However, the heavy metal content of biomass is much lower than that of coal, and as such emission of these elements from co-firing coal with biomass may not be of great concern. In contrast, SRFs are often characterized by a significantly larger amount of potentially toxic elements (PTEs) concentration than coal (Wu et al., 2013). PTEs (e.g. antimony (Sb), arsenic (As), Pb, chromium (Cr), cobalt (Co), manganese (Mn), copper (Cu), nickel (Ni) and Vanadium (V)) content in fly ash may result in the emission of their volatile fractions and the containment of their non-volatile ones in bottom ash, leading to environmental implications (Wrap, 2012). This may increase the likelihood of heavy metal emission from the co-combustion process, presenting potentially important environmental and social implications (Frandsen et al., 2011).

In addition, it has been reported that low concentrations of Cl in flue gas may potentially lead to the formation of dioxins/furans during the cooling process. Nowadays, most industrial operational units are equipped with activated carbon injection (ACI) systems, which induces the attachment of volatile compounds to activated carbon particles, aiding their removal from the gas stream (Wu et al., 2013).

Emissions of dust are reported to increase during biomass and SRF co-firing with coal, but the increase is potentially related to a reduction of the collection efficiency of the electrostatic precipitator (ESP), rather than the increased formation of ultrafine particles (i.e. particles with less than 100 nm diameter) (Frandsen et al., 2011; Lighty et al., 2000; Wu et al., 2013). Ultrafine particles can potentially affect human health and contribute to climate change due to their ability to absorb light and act as cloud condensation nuclei (Zhang et al., 2005). They may enter the body through the layer of cells lining the alveoli (air sacks) of the lung, where they may be deposited deep in the lung by diffusion (Lighty et al., 2000). Nonetheless, research is still ongoing with regards to understanding their impacts.

4. Discussion

The co-firing of biomass and SRF with coal has emerged as one of the most important interventions in power plants. This is owing to the reduction of air pollution (e.g. CO₂, NO_x and SO₂ emissions) through exploitation of at least partially carbon neutral sources of energy, and the recovery of value from materials of poor technical quality that would otherwise end-up in landfills. The reduced cost of SRF and biomass (depending on from where it is sourced) compared to that of coal and the receipt of potentially available incentives from renewable obligation certificates (ROCs), and climate change levies (CCL) due to the use of renewable energy sources, are additional benefits that make co-firing an appealing option.

Yet, the diverse physical and chemical properties of biomass and SRF have been reported to result in a number of technical implications that reduce the overall performance of the co-firing process, while presenting implications in other domains of value. These implications can be distinguished into two categories based on i) physical (e.g. MC, bulk material handling, particle size, distribution and shape, and feeding systems) and ii) technical (e.g. carbon, hydrogen, oxygen, chlorine, alkali and alkaline earth metals, nitrogen, sulphur, and heavy metals) characteristics of the fuels. Specific details as to the technical implications that each category can pose to the co-firing processes is as follows:

- Physical characteristics: result in technical implications that could potentially be easy to deal with, due to a suite of technologies and pre-treatment processes that can appropriately address these implications. An important drawback associated with the introduction of such systems is the high investment costs alongside the high risk of biomass and SRF supply security, and of changing political landscape that may introduce stringent measures on the way waste fuels (e.g. SRF) and biomass are used in power plants.
- Technical features: result in technical implications that are the most difficult to deal with as these are inherent to fuel types (e.g. C:H:O ratio), and are manifested through the synergistic relationships of their various compounds under varying conditions (e.g. temperature, loading rate, technology used etc.).

With regard to the C:H:O ratio, the more reduced the carbon contained in the fuels is, the higher their NCV would be. Biomass due to its high carbohydrate content, has a lower calorific value than coal, and thus a large amount of it is required to provide the same energy demand. This results in increased logistic costs (e.g. transport, storage and handling) and numerous hidden environmental and social impacts associated with the supply of biomass including the use of marginal land for growing bioenergy crops. The NCV of SRF depends on the varying proportions of its waste fractions (with plastic being the most favourable). However, the variety of wastes streams used for its production, seasonality aspects and types of technologies used in the production facilities are only some of the factors that make the predictions on SRF characteristics uncertain. Where high quality fuel is in demand, for example, this could bias the waste management supply chain towards SRF production rather than e.g. recovery and recycling of materials (Agraniotis et al., 2010; Di Lonardo et al., 2012; Hilber et al., 2007a; Montané et al., 2013; Rada and Ragazzi, 2014; Rotter et al., 2004; Samolada and Zabaniotou, 2014; Velis et al., 2010; Wagland et al., 2011).

The synergistic effects of Cl, alkali and alkaline earth metals, sulphur and silicate and of potentially toxic metals and metalloids have been shown to impair the combustion equipment and degrade the quality of slag, fly ash and flue gas. This in turn may lead to environmental, economic and social implications,

associated with emissions and fly ash disposal and increased operational and maintenance costs. One of the implications that stands out is the degradation of the quality of fly ash, owing to the resultant 'costs' associated with the disruption of the symbiotic relationship between power generation and concrete production industries. Such a disruption, may not only result in the disposal of PFA in land leading to potential environmental degradation, but may lead to an increase in the use of cement – a material that accounts for approximately 5% of global CO₂ emissions (IPCC, 2007) or the imports of PFA from elsewhere where co-firing processes are not used; thereby leading to a number of hidden environmental, economic and social implications.

Attempts to remediate technical limitations of the co-firing process, have largely been focused on the use of additives to stabilise and remediate the synergistic effects between the various constituents. Yet, the selection of the appropriate technology for the co-firing process and the right fuel blend are considered to be important prerequisites in the efficient operation of the co-firing process. However, in the case of SRF, selection of an appropriate technology appears to be challenging due to the highly heterogeneous nature of the fuel. The different waste streams used for its production, the variety of sorting technologies, as well as the elements and/or substances (additives, chlorine, PVC, etc.) that may be present, not only affect its quality but also its systematic production. In addition, the organisational and political aspects faced by an energy producer that intends to recover energy from waste; the uncertain regulatory climate that brings up changes in the waste recovery processes and the end-of-waste criteria that largely govern the production and use of SRF; the uncertainty regarding unresolved technical challenges (e.g. reliability on quality, availability of feedstock, effects on maintenance costs, etc.) and its insufficient marketability, are additional obstacles associated with the uptake of SRF as a co-firing fuel (Garg et al., 2009).

In the case of biomass, fuel characteristics are more stable compared to SRF and thus the selection of the right technology and fuel blend may generate varying opportunities for maximising the recovery of its value. Nonetheless, issues associated with the sourcing of biomass and its availability, especially when reliance is largely dependent on agricultural and forestry residues, and the large investments costs associated with optimum process performance, are critical in assessing the bioenergy potential of the co-firing process.

Regardless of the co-firing configuration, the technologies used for the milling and burning of biomass, SRF and coal, the physico-chemical characteristics of the fuels and fuel blends, the sustainability of the process can only be assessed via a holistic evaluation of the technical, environmental, economic and social aspects. In this study we have taken a first step towards this by identifying the links between the technical properties of the fuels and their co-firing effects elsewhere in the system e.g. on the long-term operation and maintenance of the power plant, on the increased or reduced severity of emissions to air and land, and on the ability of connected systems (i.e. concrete manufacture) to recycle by-products. In each case, there are complex interactions between a wide range of technical properties and the social, environmental and economic benefits and impacts, and benefits realised in one part of the system need to be balanced against impacts in others.

5. Conclusions

While co-firing has emerged as one of the most important interventions in power plants, it may also result in hidden impacts that are overlooked. When co-firing, the physical and chemical properties of the mixed fuels and the subsequent technical implications on the process performance and by-products are significant.

Environmental pollution caused by soot, PAHs and dust emissions and associated effects on human health; increased operational and maintenance costs required for mitigating corrosion effects on the combustion equipment and handling PFA that can no longer be used by the concrete production industry; the need for large investment costs associated with the shipping, storage and handling of biomass and SRF owing to their low bulk densities; are some of the implications that have been underpinned as a result of the technical implications of co-firing.

Attempts to deal with these implications are often unjustified, largely because of prevalent partial, non-systemic approaches adopted that seek to provide short-term environmental and economic solutions, whilst neglecting to account for implications in the wider context and in the medium- to long-term. Yet, advising on the 'real' sustainability of the direct co-firing of biomass and SRF with coal requires a systemic approach in order to transparently assess the benefits and impacts associated with it, and provide solutions that seek to maximise recovery of value across multiple domains. However, our findings at this early stage are necessarily narrative and disjointed; hence, in aiding the selection of useful metrics (quantitative or semi quantitative descriptors) for multi-dimensional value assessment and its distribution amongst interconnected resource recovery systems considerable further research is required. This would produce a coherent analysis framework that can fully capture the potential economic, environmental, and social impacts associated with co-firing interventions regardless of the technologies used, as hidden implications may lurk even in the seemingly most sustainable and viable solutions.

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