BIOMASS AND BIO-ENERGY UTILISATION IN A FARM-BASED COMBINED HEAT AND POWER FACILITY

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ABSTRACT: Five different renewable energy technologies located at an agricultural and environmental research centre in Northern Ireland, were monitored to assess the cost, performance and efficiency in real-time operation of solar and bio-energy produced from crops and farm wastes utilised for energy generation in industrial grade equipment. Monitoring was conducted over a six year period, with power units running simultaneously or intermittently according to demand from the local district heating system. The purpose of the work was to investigate fossil fuel (oil) displacement, carbon dioxide emission (CO₂e) reductions, financial and environmental sustainability of these technologies in a farm based scenario. Between 2009 and 2014, total heat output from the centre was 7,750 MWh with contributions of 47.2 %, 17.1 %, 9.8 % and 13.5 % from the biomass, biogas, multi-fuel boiler and biogas CHP unit respectively. Solar thermal produced 0.49 % and the back-up oil boiler 11.9 %. Total electrical output was 572.6 MWh with 95.2 % generated from biogas CHP and 4.8 % from the solar PV system. Fossil fuel and average CO₂e reductions ranged from 20.1 % to 54.1 % and 23.3 to 55.7 % respectively, reductions that combined with financial savings to present a viable and sustainable renewable energy system.

Keywords: Energy Farm Biomass Biogas Solar CO₂

1 INTRODUCTION

The increasing demand for renewable sources of energy for heating and electrical power generation, has been driven by a number of factors but largely by rising costs, fuel security issues and increasingly, environmental concerns [1, 2]. The European parliament has been instrumental in addressing these issues across all its member states and seeks to increase the uptake of biomass for energy generation and greenhouse gas (GHG) emission reductions [2]. While this may encourage interest and uptake of sustainable and renewable energy generation, there is often a mismatch in fuel availability and power plant suitability [2,3]. Between the extremes of small scale domestic and large scale regional heat and power generation, there is often a need for intermediate sized plants and this may be particularly applicable for farm based agricultural

enterprises [4, 5]. Mixed farms, such as those that have both livestock and arable capabilities, can offer high potential for both electricity and heat generation from animal wastes and crops grown specifically for energy crops. Anaerobic digestion (AD) can utilize animal wastes and crops, such as grass silage and maize silage, to produce biogas that can then be used for heat and/or electricity production. A significant and growing number of such plants running on these fuel types are already installed on farms across Europe [6, 7]. Farm buildings and their environments are often also particularly suited for solar heating and electricity production [5]. Electricity producing solar photovoltaic (PV) and heat producing solar thermal panels offer reliable and relatively continuous (during daylight hours) electricity and hot water production and are particularly suitable for farms [5]. Heat from biomass is dominated by wood fuels, from waste streams (forestry, sawmill, furniture manufacturing) and dedicated wood crops, particularly short rotation (3 year) coppice (SRC), primarily willow (*Salix spp*) and short rotation (12 to 15 + years) forestry crops such as poplar (*Populus spp*) and eucalyptus (*Eucalyptus spp*) [5,8]. However, herbaceous crops, such as miscanthus (*Miscanthus spp*) commonly referred to as elephant grass, are also gaining acceptance as alternative fuels for combustion [9].

These types of modern renewable energy technologies are often installed as stand-alone plants though combined technology plants may be feasible on farms, both for primary energy supply and as a potential diversification into energy (heat and power) export [5,10,11]. Where such combined energy generation plants might be installed, comprehensive computerised energy management and control systems may be essential for reliable and overall efficient performance [10,12]. However, the critical challenge for such on-farm renewable energy schemes is to achieve viable economic energy production that is environmentally sustainable and reduces GHG emissions [10,11].

Agriculture is responsible for an estimated 28% of Northern Ireland's (GHG) emissions and the regional production of electrical energy (from mainly coal and natural gas) contributed 18.8% to total 2011 GHG emissions [13]. In the United Kingdom (UK) targets for GHG emissions reduction (35%), fossil fuel substitution and higher renewable energy reliance have led to an increased interest in renewable energy technologies. The adoption of renewable energy technologies is a mitigation strategy that has the potential to reduce emissions by replacing fossil fuel consumption and a number of incentives have been developed to enable this goal to be achieved. Currently, there are uncertainties regarding the impact of changes in farming practices on emissions from renewable energy crops and the utilisation of conversion technologies. Concerns also exist over potential conflicts between land used for fuel rather than food and the subsequent mitigation of GHG emissions by producing and utilising such energy crops for heat and/or electricity [14].

The aim of this paper is to describe and assess the measured outputs and overall performance of the inter-linked and wholly contained multiple energy production units on a large scale farm and environmental research centre in Northern Ireland. Further objectives of this study are to estimate the fossil fuel use reduction, GHG emissions and carbon savings of the research centre from its activities during a period of 6 years. This follows the adoption of renewable energy technologies in 2008 to substitute a significant proportion of fossil fuel use.

2 MATERIALS AND METHODS

2.1. Site description

The schematic (Figure 1) shows the outlay of the purpose built energy centre located within the research farm estate of the Agri-Food and Biosciences Institute, (AFBI) at Hillsborough (54.4° N and 6.0° W) in Northern Ireland.

Figure 1 here

The research farm estate has 310 ha of land with a total grassland area of 292 ha used by dairy, beef, sheep and pig production and 10 ha for biomass crop research (Figure 2). There is also ~ 200 ha of mixed broadleaf and conifer woodland, the latter being largely commercial forestry stock. The Energy Centre building (370 m²) which was constructed in 2007/8, is a double height block and steel construction designed to meet national building standards and fire containment specifications. The building contains all the energy production units as detailed (Figure 1). Developed primarily as a demonstration facility for commercial standard on-farm renewable energy technologies, the centre also provides facilities for renewable energy and environmental research. The technologies installed were solid biomass thermal conversion units, an anaerobic digestion plant for biogas production from cattle slurry, a biogas powered combined heat and power (CHP) plant for heat and electricity production and solar generated electricity and thermal energy. A district heating system was also installed for heat distribution while new electrical systems were installed for connection and integration of renewable electricity to the mains network. Along with this development a major refurbishment was completed of existing offices and conversion of old agricultural buildings to office and corporate facilities that were eventually linked to the district heating system. A schematic of the general farm area, buildings, biomass crop areas and district heating loop connections to the renewable energy centre is shown in Figure 2.

Figure 2 here

2.2. Electricity and heat generation

The normal heating and electrical base loads of the whole farm and research centre in 2008 were $\sim 600 \pm 250$ kW and 100kW respectively with consistent seasonal electrical demand (150 kW peak summer, 250 kW peak winter). Heating was originally supplied solely from 18 oil boilers attached to various buildings throughout the farm estate. Based on an economic appraisal of heating oil use from 2003/4 to 2005/6, it was estimated that biomass energy systems capable of replacing ~80% of heating oil ($98.5 \pm 20.8 \text{ m}^3 \text{ y}^{-1}$) offered the best economic incentive for such systems, providing heat to all but two

outlying buildings. Electricity generation was assessed against known usage and potential biogas outputs from anaerobic digested slurry from the farms 360 (± 15) cow herd. Initially, a 50 kW electric and 50 kW heat output combined heat and power plant (CHP) unit designed to run 12 hours per day, 250 days per year (daytime only) was planned. However, uncertainties relating to outputs and reduced capital funding, resulted with investment in lower capacity CHP unit running 24/7 x 52 weeks (with 6 x 0.5 days shut down for maintenance). Both electrical and thermal projections were interpolated with an 20% optimism bias to allow for drift.

The electrical and heat generation units consisted of a 23 kW + 40 kW combined heat and power (CHP) unit (Tedum T25-Premi F25) respectively and a heat only 120 kW boiler (Hoval Atmogas) both designed for biogas fuel only. Biogas was produced from an anaerobic digester (AD) plant (Greenfinch Ltd) run on dairy cow slurry (20 t d⁻¹ through put capacity) with facility for herbaceous material inclusion. Solid biomass fuels were combusted for heat generation in a 320 kW woodchip boiler and a 120 kW (nominal output) biomass multi-fuel boiler, each auger-fed from demand activated 10 tonne and 3 tonne (respectively) feedstock hoppers.

Additional electric power was provided from a 11.9 kW solar photovoltaic system composed of 70 x 175 W panels (Schuco S170 SP3) arranged in 7 x 10 panel strings mounted on tubular frames angled at 35° tilt and facing south. The direct current (DC) created was converted to alternate current (AC) by inverter units (SMA SB1700) and fed into the energy centre electrical mains system.

Electrical power from the CHP was connected directly with the local grid mains supply. Thermal energy was used to provide space heating and hot wash-water for offices and buildings. To meet heating peak load demand and provide a back-up facility a 660 kW oil boiler (Buderus Logano GE 615) was also installed.

Separate from the energy centre building, two small (2 x 2.5 kW) thermal solar units (Kingspan, DF100) each with a 1 m³ insulated water tank, were integrated in the dairy parlour to pre-heat cold mains water to be used for the milking parlour equipment sterilization system. The sterilisation system required 2 x 1 m³ litre per day of water at > 95°C, heated by a (102 kW) oil boiler (Andrews DFS90). Solar pre-heating was designed to reduce oil consumption by the boiler.

The largest heat source was from a woodchip-only boiler (Figure 1) that had a capacity to deliver up to 320 kW of heat for offices and production buildings, via hot water pumped through a 2.8 km long district heating loop (flow and return) of highly insulated thermal pipe (Uponor, Eco-Flex). This consisted of 2 x 50mm diameter ($\varnothing$) main flow pipes (3.59 kg m⁻¹) capable of bearing temperatures to 95 °C, and pressures up to 600 kp, connected by 25mm $\varnothing$ flow and return off-shoots to networked buildings. This also provided the heat necessary to maintain the mesophillic anaerobic digester [6,10] feedstock tanks at a constant temperature (37.5 °C). Hot water from all heat sources was mixed and stored in a 9 m³ insulated tank (Figure 1) with circulating water maintained at ~75 °C that also supplied the hot water for offices and staff cleansing facilities throughout the farm estate, including eventually the refurbished & converted buildings. The 120kW multi-fuel biomass boiler, which was designated for experimental research, was also fully integrated within the heating system and was also employed occasionally for continuous heat production. Altogether the new heating systems replaced 14 of the original oil fired heating boilers. All units were integrated to the flow and return heating loop, operated at a set pressure (1.3 kp) driven

by a series of electric pumps (WILO, 2.2 - 2.5 kW) each unit with an average operating flow rate of 1.7 L min^{-1} . The installed renewable technologies and their rated output capacity (at full load) are shown in Table I.

Table 1. here

Energy production was demand led and controlled by the computerised Buildings Energy Management System (BEMS) using real time information. An ethernet based peer-to-peer communications controller (Cylon, UC32.netK) was installed to network Unitron UC32 field controllers linked to the energy system monitors. This collected and recorded data from on-line and in-line electrical and thermal monitors and meters at specific input and output points on the system. Heat generation, water flows and pressures were measured by meters (Kamstrup multi-cal L60) located on each individual unit and all data was recorded on the BEMS. Electricity generation was measured using integral power meters and recording equipment.

Woodchip fuels were generally delivered fresh with a moisture content $> 25\%$ (mass fraction), requiring drying in the 320m^3 storage capacity drying bays located adjacent to the energy centre. Drying was effected with air drawn through 200kW heat exchanger units and heated to $\sim 10^\circ\text{C}$ above ambient, by fans (Typhoon TC4) powered by 22 kW electrical motors, propelling air flow at $650 \text{ m}^3 \text{ min}^{-1}$ at 10 pa pressure, forced via a plenum and mesh vented floors up through the fuel piles. Woodfuels were normally dried to moisture content (mass fraction) within the 20 – 25% range. Purchased fuels were supplied by local woodchip producers located within a 50 km radius of the centre.

Plant commissioning and testing began during August of 2009, the initial year of operation for all the renewable technologies. Biomass heat and biogas electricity with heat production started in September 2009 and CHP electricity and heat production stopped (temporarily) in August 2014. It is important to emphasise that although maintenance and repair schedules were present in all years of operation, local and business needs were within a set budget and prioritised in such a way that all the renewable energy systems were, with the exception of AD operation, given a low ranking, resulting occasionally in long periods of down-time (inactivity).

All farm energy budgets, production, energy use, CO_2 emissions and running costs, were collated on a financial years (1st April to 31st March) basis. Therefore values in graphs and tables are stated in this standard accounting period unless otherwise shown. Capital costs are not discussed as they were not reflective of normal industrial development, due largely to funding source imposed financial overheads (oversight and capital controls) and installation of high specification (scientific standard) metering, monitoring and recording equipment and devices.

2.3. Biomass feedstocks

The primary feedstock for the anaerobic digester was cow slurry (average $7,300 \text{ Mg y}^{-1}$) from the 350 cow dairy herd and latterly, supplemented with grass silage during 2011-12 and 2012-13 respectively. Since commissioning in 2008-9, the woodchip boiler had been running 24 hours per day, 7 days per week for long periods on a variety of woodchip types,

produced both on-farm and of local provenance (Table II). These were mostly 3 year-old SRC willow woodchip, harvested by either one-pass cut and chip machinery (Class willow harvester) or whole rod harvested (Stemster harvester) crops that were stacked for open air drying (normally 6 months) then chipped. Conifer log woodchips were produced on site from clear-fell harvested (Valmet 901 single grip harvester) stands of 40 year old Sitka spruce (*Picea sitchensis*. L. sp.) and Lodgepole pine (*Pinus contorta*. L. sp) from the farm forests. Forest residues (brash) were also recovered using a brash baler (John Deere 1490 Slash Bundler) on the clear-fell sites [15]. A mobile wood chipper (Starchl MK47-600) was used to comminute these materials on site for forced air drying in the drying bays to produce usable fuels [15]. Descriptions of the main fuels used are shown in Table II. These fuels were also occasionally combusted in the 120kW multi-fuel boiler which also was used to test small quantities of commercial grade wood pellets, woodchip from different tree species, herbaceous crop fuel miscanthus [16] and other potential biomass fuels such as grass silage and waste animal feeds produced on the farm. All solid biomass fuels (wood and crop derived) were sampled at delivery using CEN/TC 335 biomass standards [17] for moisture/dry matter content (mass fraction) and particle size distribution (% mass fraction), factors that determined fuel quality and price. Standard conversion factors (energy density by mass) were used for heating oil, (11.7 MWh Mg⁻¹), SRC woodchips (3.5 MWh Mg⁻¹) and log wood (4.1 MWh Mg⁻¹) fuels (wood fuels at 30 and 20% moisture content (mass fraction) respectively) for energy output calculations [18].

Table. II. here.

2.4. GHG emission reductions

The GHG emissions were expressed as global warming potential according to IPCC (2006) and defined as CO₂ equivalent [19]. The system boundary was set at the research centre gate. The estimate of CO₂e reductions according to Equation [1] was based on baseline fuel usage following the IPCC guidelines using the generic application of an emission factor that represents the activity parameter and fuels. Emissions resulting from field operations, transportation of the fuel, construction and maintenance of farm buildings and roads are excluded because of a lack of specific and accurate data. For the purpose of this exercise biomass fuels are assumed to be CO₂e neutral, as presented in other studies [11]. In addition the CO₂e emissions were estimated by multiplying the annual amount of fuel from each farm activity by the default emission factor provided by the IPCC (2006) using the IPCC tier 1 approach [19] and subsequently compared against the energy source most likely to be displaced.

Equation 1: Formula for carbon dioxide (CO₂e) emission estimation:

$$Emissions (CO_2e) = \sum_a (Fuel_a * EF_a)$$

(a = type of fuel (heating oil, diesel), EF = emission factor)

3. RESULTS

3.1. Electricity from Biogas

Electricity outputs from this unit were generally maintained due to the continuous supply from the AD system with excess gas being used in the biogas boiler for heat. Until 2011 the plant digested an average 20 Mg d⁻¹ cattle slurry (average 6.9% dry matter mass fraction) producing an average biogas output of 15.2 m³ Mg⁻¹ slurry with an energy value of 85 kWh. By comparison fresh grass silage was found to have significantly higher energy content than dairy cow slurry, on average grass silage with 21% (mass fraction) dry matter, produced methane at 63 m³ Mg⁻¹ with an energy value of 630 kWh. From August 2011 to January 2012, a slurry only feedstock and a slurry + silage feedstock (19.8 Mg + 0.7 Mg respectively) produced 312 and 414 m³ d⁻¹ biogas respectively. The methane proportion of the biogas was 55.7 and 50.5% (mass fraction) respectively; a reduction of 5%. However, this decrease in methane concentration was supplemented by the overall increase in total methane production from 174 m³ d⁻¹ for the slurry only feedstock, compared to 208 m³ d⁻¹ from slurry + grass silage. For the same period in 2012-13, the addition of 1.7 Mg d⁻¹ grass silage with a dry matter content of 24.9% (mass fraction) to the slurry feedstock increased biogas production to 603 m³ d⁻¹ though feedstock volume remained constant. The methane component of the slurry + grass silage biogas was again lower (3%) than for raw slurry but the methane production was 82% higher (317 m³ d⁻¹). When run on a constant 24 hour productivity basis the CHP unit could produce 0.55 MWh d⁻¹ of electricity. For a full productivity year (362 days) maximum potential output would have been 199.8 MWh y⁻¹. However outputs varied from year to year (Figure 3). The 2009-10 year provided approximately 8 months running time and included commissioning and testing. The final year (2013-14) saw the cessation of CHP generation after 4 months. Outputs increased between 2009 and 2012, attaining a maximum of 150.8 MWh during 2011-12, reducing the following year to 129.4 MWh.

Figure 3: here.

3.2. Solar PV Electricity

Electricity output from the solar PV system totaled 31.8 MWh between 2010 and 2014 (Table III). Electrical output for 2010-11 was low due to loss of production caused by water ingress to cabling connecting the inverters, with a similar fault to one inverter during May-June 2012.

Table III. Here

The fluctuations seen in the total cumulative outputs from the PV reflected those observed in the monthly values for the system (Figure 4) with the average monthly output of 765.1 ± 191.4 kWh between 2011 and 2014. During the winter months outputs were seen to fall to very low levels (Figure 4) with outputs approximately 10% of summer totals.

Figure 4: Here. .

3.3. Heat from Biogas

Biogas heat generation totaled 1356.3 MWh for the periods 2009/10 to 2013/14, showing yearly increases until 2012-13. Highest amounts (733.3 MWh) were generated in the 2012/13 period as shown in Figure 5. Also, the increase in heat production from the biogas boiler from 2013 onwards, reflected reduced CHP unit productivity (Figure 5) and increased biogas boiler running times and also the increase in gas quantity produced by the AD plant (see Section 3.1).

Figure 5: here.

Biogas production from the AD plant was continuous and during CHP and biogas boiler downtimes, particularly during the latter half of 2012-13. During these periods of CHP inactivity, AD biogas production resulted in large volumes of unused gas (33640 m³) that had to be flared-off. The lost heat potential from the flared-off biogas was equivalent to 185 MWh.

3.4. Heat from Biomass

Total heat outputs for the solid fuel biomass boilers were 4358.2 MWh from 2009 to 2014 (Figure 6). Outputs from the 320 kW woodchip boiler showed a continuous yearly increment from 2009 (561.2 MWh) to 2014 (937.2 MWh) despite several month long down-times in some years. The total production for the period was 3627.5 MWh. Production from the multi-fuel boiler (752.3 MWh) included periods when it was operated full time for direct heat production and during periods of experimental work.

Between September 2009 and April 2013, the wood and multi-fuel boilers consumed 1,353.4 Mg of woodchip and ~ 8 Mg of other biomass fuels. This produced 3,804.4 MWh of heat, maintaining waters to the required temperatures (75 °C). Fuels used were normally within the moisture range of 20 to 30% (mass fraction) though raw and delivered fuels varied. Dry matter content (mass fraction) averaged $56.9 \pm 17.8\%$ between fuels with fresh harvested woodchip averaging $48.4 \pm 5.3\%$ (mass fraction) compared to purchased woodchip which was generally supplied pre-dried ($80.8 \pm 5.9\%$ mass fraction). Locally produced and purchased woodchip with moisture $> 25\%$ (mass fraction) had to be forced-air dried on-site. Examination of fuel particle size distribution (by percentage weight, mass fraction) also showed significant differences ($p < 0.001$). The most prevalent size (averaging $73.2 \pm 5.5\%$ mass fraction) was within the size range $> 6.3\text{mm}$ to $< 25\text{mm}$ while fine particles ($\leq 3.15\text{mm}$) composed on average $8.6 \pm 2.1\%$ (mass fraction).

Figure 6: Here.

Examples of measured loads and outputs from the 320 kW boiler, operating under normal conditions and combusting four different woodchip fuels, are shown in the following (Table IV). Based on the moisture content (mass fraction) of the four fuels (Table IV), the realizable calorific value [20] of the four fuels would have been 4.3, 4.6, 3.5 and 3.8 MWh Mg⁻¹ respectively. Set against those values, the actual outputs represent fuel conversion efficiencies of 71.3, 65.2, 74.1 and 68.3 % for the respective fuels. Grate and fly ash production from the fuels (dry weight) was very different. The conifer forest residues and willow woodchip produced ash equivalent to 1.3% and 1.2% respectively of total fuel load. The mixed conifer (whole tree) & willow woodchip fuel and the stem harvested willow woodchip fuel produced 0.5% and 1.2% ash respectively. The large differences observed in the time periods relative to the fuel consumption ($1.1 \pm 0.5 \text{ Mg d}^{-1}$) demonstrate the changes in demand that controlled the 320kW boiler operation. These variations in demand were seen during all years (Table IV) and were attributed largely to climatic conditions though inoperation of other energy production units also contributed.

Table IV: Here.

3.5. Solar heat

The small solar thermal collectors produced 21682 and 21311 kWh of heat from unit 1 and 2 respectively in the years 2009/10-2014/15. In total solar unit 2 produced more than unit 1, however unit 2 produced more in the early years (2009-2012) of introduction but showed a decline in output and in the later period (2012-2014) panel 1 was the major producer (Figure 7).

Figure 7: Here.

The solar heat collected in the water tanks reduced oil heating required to attain water temperature (95 °C) and this heat contribution led to a reduction in oil use (Figure 7) by the milking parlour sterilization system. Reductions ranged from 15.3% (2011-12) to 43.4% (2013-14). The oil quantity used dropped from the pre-solar installation year (2008-9) and remained considerably lower in each succeeding year. Despite higher solar panel heat outputs between 2010-11 and 2011-12 there were slight increases in oil use compared to 2008-9. These increases were known to be due to higher demand for heated water sterilization in these years (Figure 7).

3.6. Total heat outputs

The total heat output generated between 2009 and 2014 was 7750 MWh from all sources with renewable contributing 6787 MWh (Table V). This includes the heat generated from the back-up oil boiler and the dairy unit solar heat supplemented boiler. The largest single contributor to heat production was the woodchip boiler (Table V) while the CHP produced the second largest amount of heat during 2009 to 2011. The total production from renewable sources was greater than that from oil in every single year and by a factor of 7 over the full term (2009 to 2014).

Table V. here.

Based on the pre-EREC heating oil use ($152.7 \text{ m}^3 \text{ y}^{-1}$) for the 2008-9 year, over the 5 year period total oil saved was estimated at 280.7 m^3 representing an average reduction of $56.1 \pm 8.1 \text{ m}^3 \text{ y}^{-1}$ ($36.8 \pm 14.6 \%$ per year). However the total heat output from renewables averaged 1357 MWh y^{-1} , providing an excess of 798 MWh y^{-1} over the oil use reduction shown for the period and represented an offset in heating oil use equivalent to $80.2 \text{ m}^3 \text{ y}^{-1}$. This was a direct result of the extra heat demand from the contemporaneous office developments and anaerobic digester heating line that were integrated into the district heating loop. The first year (2009-10) heat usage (9 months) by the AD plant alone was 176.6 MWh with the full year average thereafter of $229.1 \pm 18.6 \text{ MWh y}^{-1}$ from 2010 to 2014. The remainder of the produced heat was distributed by BEMS controlled demand to individual buildings for space heating and ablution facilities.

3.7. Cost savings and CO_{2e} reductions

The reductions from heating oil use due to the contribution from renewable heat production, based on the energy centre heat outputs from 2009-10 to 2014, were compared with heating oil use (152.7 m^3) for the oil-only heated 2008-9 year and were found to have resulted in significant overall savings in energy costs (Figure 8). Sensitivity analyses, which included changes in oil and biomass prices, showed that fluctuations and increases in oil use in some years (Figure 8) were due solely to non-productive periods for the renewables systems. Over the 5 year period (2009 - 2014) total oil saved was estimated at 280.7 m^3 representing an average reduction of $36.8 \pm 14.6 \%$ per year compared to the pre-renewables year (2008-9). Based on the 2008-9 oil costs, the estimated reduction in oil costs averaged $\text{€}44,100.0 \pm \text{€}16,240.0$ per year. Woodchip fuel costs varied considerably from 26.5 € Mg^{-1} (Brash) to 136.2 € Mg^{-1} (dry woodchip- delivered) with the average SRC willow cost of 64.0 € Mg^{-1} . The resultant fuel financial savings based on oil reductions and biomass woodchip fuel costs, were estimated to total $\text{€}176,400.0$ over the period 2009-14. The extra heat output produced from the renewables provided a further offset in heating oil use ($80.2 \text{ m}^3 \text{ y}^{-1}$) that reduced oil costs by a further $16,240.0 \text{ € Mg}^{-1} \text{ y}^{-1}$ at the same oil prices.

Figure 8: Here.

Greenhouse gas emissions, contributed as CO_{2e} emissions calculated for each fuel type, were also seen to advantage the renewable technologies with significant reductions accumulated (782 Mg CO_{2e}) over the whole time period (2009 – 2014). This was seen in each year (average $196 \pm 17.8 \text{ Mg y}^{-1}$) to be directly related (Figure 7) fossil fuel displacement by biomass as was the total carbon saving. Figures. 8 and 9 provide an overall trend of the level of GHG emissions from heat and power. In 2009, heating accounted for 6.4% of total GHG emissions in the Research Centre. Since 2008 there has been an overall decrease in the volume of fossil fuel for heating used, with some year on year variation. The increase in emissions in some years is directly associated with the increase in consumption of fuel due to stand-down time of the renewable technologies resulting in increased fossil fuel use. The CHP unit, utilising biogas from the anaerobic digester, supplied approximately 40% heat to meet additional load requirements of the site. Data from the BEMS shows that the site had a continuous electricity base load average requirement of 1500 MWh y^{-1} . The research centre had consumed 1400 MWh of electricity in 2014, which has decreased by 12.7% relative to the baseline year. On average 8.25% of this electricity was generated using renewable energy sources since the baseline year (Figure 9). In addition, carbon dioxide emissions from power were reduced by an estimated 100 Mg from baseline year (Figure 9).

Figure 9: Here.

4 DISCUSSION

4.1. Electricity production and usage

Electrical output from the CHP unit totalled 572.6 MWh for the reported years with an average monthly output of the unit $10.2 \pm 2.6 \text{ MWh}$. The unit often ran for long periods (up to 60 days) for an average $16.3 \pm 2.5 \text{ h d}^{-1}$, often without interruption and fault at near full load capacity producing at an average rate of $21.5 \pm 0.5 \text{ kW}$, indicating that the gas quantity and quality was sufficient and consistent, as reported previously [21,22]. The CHP power generation ended in December 2013 due to engine failure and unavailability of spare parts. The engine-generator had by this time accumulated 26,264 running hours.

Electricity production from the PV system, totalling 31.8 MWh, was relatively consistent, with the exception of year 2010-11 (Figure 4) and despite ~ 20% of the unit surface area suffering partial shading, which has been shown to reduce outputs [23]. During May of that year, water penetration of external cable connections caused damage to 4 of the inverters,

resulting in the large reduction of potential electrical production. Contrasting duration of daylight and light intensity with electrical output data, clearly showed that these were the determining factors in PV productivity similar to results from other studies [23,24]. On-site PV records of the total daylight hours indicate that approximately 30% are sunny and the remaining are cloudy or with low sun intensity. The average efficiency of the PV system (2011 – 2014) was estimated at 0.77 ± 0.07 of peak potential. Allowing for down-time variations between years, this was similar to findings reported for other PV systems [23,24]. These results also showed that although total productivity was lower here, due to shorter hours of daylight than in more southerly located solar installations, the general insolation conversion efficiency was of a similar value [23,24]. Overall the combined CHP and PV electrical outputs produced small reductions ($8.7 \pm 3.6\%$) when set against the total consumption (6717 MWh) of the farm estate (Figure 10) with PV system outputs in the final 3 years particularly consistent and reliable. The total renewable electrical generation was 572.6 MWh with 95.2% from CHP and 4.8 % from PV.

Figure 10: Here.

4.2. Heat production and usage

The 320 kW woodchip boiler outputs almost doubled from 561 MWh in 2009 to 937 MWh by 2013-14. Despite losing 10 months potential productivity due to down-time during the last 4 years, the yearly output average was 725 MWh. Productivity varied considerably with daily averages ranging from 0.14 to 0.26 MW though within daily averages, especially during daytime peak heat demand, outputs up to 0.29 MW (~80% of maximum capacity) were recorded, indicating high levels of combustion efficiency. The major influence on combustion efficiency was in fact seen to be the demand led control system whereby even at peak heat demand times, once temperatures were achieved, demand on the boiler cut back automatically. Also, during low heat demand periods, most especially at summer times, the boiler was often in slumber mode ie; alight but barely ticking over until heat demand increased, operating methods known to decrease efficiency and increase flue gas emissions of air pollutants [25,26,28]. The total heat produced by the woodchip boiler from 2009 to 2014 was 3627 MWh.

The 120 kW multi-fuel boiler, though run infrequently, produced very efficient levels of output, consistently achieving its rated maximum output of 120kW. Used primarily for experimental work, with over 16 months of inactivity or short (2-3 hour) test runs, the unit still accrued 725 MWh (Table V). Run chiefly on woodchip fuels, other fuels including commercial grade pellet and chipped miscanthus (*Miscanthus gigantea*) fuels were also reported to combust efficiently [16].

The oil boiler was used primarily as a backup for urgent call if the woodchip boiler was inactive or to supplement outputs if demand, particularly during cold winter months, exceeded capacity of the renewable systems. Though in regular use

throughout each year, output for 2010-11 was 407 MWh and in later years that declined, with the yearly average and total heat from oil of 193 MWh y^{-1} and 963 MWh $5 y^{-1}$ respectively (Table V).

Heat output from biogas, via the CHP heat recovery system and the biogas boiler, was also relatively consistent (37.7 ± 3.1 kW and 80.7 ± 50.5 kW respectively). The latter years showed a large rise in biogas boiler heat production due to the addition of silage increasing gas quantity and with breakdowns and eventual close-down of the 23 KW CHP in 2013-14. The working experience and results from the AD and CHP units displayed many of the requirements for feasibility of modern AD on livestock farms [6,7]. Overall, the major heat source during the reporting period was the woodchip boiler, followed by the biogas boiler and CHP contributions (Figure 11). As a percentage of total heat output, the oil boiler produced only 12% of the total heat with 88% derived from the renewable sources in the energy centre.

Figure 11: Here.

Many factors contribute to the heat outputs from different biomass fuels, fuel dry matter, particle sizes and proportions and many other physical and chemical properties of the fuels [4,16,26,27]. In a previous study in the centre, fuels displayed significant differences in their make-up, such that woodchip, even when produced from the same processing machinery and using similar methods, differences were seen to affect boiler outputs and performance [16]. The differences in the outputs between the four fuels shown in Table IV were due to a number of factors apart from the effects of moisture content (% mass fraction) which has been shown to affect combustion right from start-up phase [25] and influences combustion energy conversion performance even at the large scale [8]. Dry matter content ($60.7 \pm 11.9\%$ mass fraction) variation between fuels and even within loads was a regular feature of raw herbaceous and wood chip deliveries, which is a common finding in many solid biofuels reports [4,26]. There was a significant difference in the gross energy found in the fuels, which was generally higher in conifers (average 20.0 MJ kg^{-1}) than willow (average 19.0 MJ kg^{-1}) similar to values reported in other studies [16,26,27]. As a result conifer derived fuels, despite having higher moisture content (by mass fraction), which can affect calorific value [25,26,27], burned with much greater intensity compared to the willow with the average 24h outputs 3.1 and 2.7 MWh Mg^{-1} respectively. Such differences were seen to be common amongst all fuels. The proportion of energy not realised, ranging 25.9 to 34.8%, was due to several factors; the boiler was regulated by demand from the heating loop, automatically increasing or reducing boiler combustion, which can affect the overall efficiency of the boiler [25,28]. There was significant heat dissipation with boiler flue gases found to exit at between 165 to 200 °C, and radiant heat loss through the actual boiler and associated equipment, as noted in a other wood combustion units studies [16,25]. There was also a small heat loss via the automated removal of hot ash from the combustion chamber though this was not measured. Generally, the 320 kW woodchip and 120kW multi-fuel boiler (which was seen to normally operate at maximum capacity) had measured average boiler efficiencies of ~85% similar to those reported in other studies [25,27]. The ash production from the

fuels, ranging from 0.5% to 1.3% (mass fraction) were typical of values expected for this type of fuel and combustion [16,26,27]. This aspect of biomass utilisation further emphasises the large and significant differences between fuels, the potential for large ash accumulations at high volume installations and therefore the need and advantages of ash disposal planning [29]. These factors have been seen in many studies of biomass fuel combustion [8,25,26,27] to affect energy conversion efficiently which, consequently, can limit the viability of biomass energy generation in smaller scale plants [4,11]. Ash residues from combustion in the boilers were mixed with manure for land spreading on land within the farm area.

While increased efficiency and performance of biomass energy systems (primarily combustion) are very much linked to scale of operations [4] the logistical benefits of localised operations with the local heating system and low fuel transport costs, that can enhance operational efficiency [4,5,29] were present at AFBI, Hillsborough. The non-homogenous nature of the biomass fuels used here perhaps demonstrate the major issue for combustion systems. Virtually every aspect of the fuels physico-chemical natures were found to be significantly different, with the consequence of different combustion and emission profiles [16]. Such disparity is the essence of the difficulties encountered in planning fuel supplies and predicting combustion performance and emissions reported in other studies [25,26,27]. Further, drying woodchip, most especially fresh, wet material, was found to add considerably to the cost of energy production [30].

4.3 Fossil fuel and GHG reductions

Overall farm estate emissions have increased by 3% since the baseline year of 2008-2009 though emissions from heat and power have decreased by 25% since baseline, but risen slightly compared to 2012 (Figure 8). This has been mainly due to work on upgrading the CHP in 2013 which resulted in more fossil fuel use. As of June 2014 a new Tedom 95 kW(e) CHP unit has been in operation and emissions from heat and electricity use for 2014/15 are expected to fall in line with 2012 values. As a result the consumption of fossil fuel varied considerably since 2008, especially in the dairy unit which maintains a significant requirement for energy. The solar panels fitted to the dairy parlour also contributed to meeting the demand for $2\text{m}^3\text{d}^{-1}$ of water at 95°C required to flush and sterilise the milk pipelines. In general, direct energy use for milk production in Northern Ireland and the rest of the UK represents approximately 20% of the total energy use and hence CO_2 output on a dairy farm [31] where consumption is dominated by milk cooling, water heating and vacuum pumps. CO_2 emissions from energy use on the farm research centre accounts for only 13.5% of total emissions. Nevertheless, while there has been a very large reduction in emissions from fossil fuels (35% oil and 13% electricity), it is proving harder to reduce emissions from livestock. However there is a variety of important factors that influence emissions, which are not covered in this current study.

The emissions derived from the use of heat and power were relatively low and varied between 3.9% and 9.7% of the total research centre level emissions. Much of this variation is related to the adoption of the renewable energy technologies in 2008. Typically on farms in the British Isles with similar livestock categories, the direct inputs comprise a small percentage of the total emissions [31,32] but comprise a greater proportion on farms with intensive livestock systems. These results are

in line with results of other studies [31,32] which suggest that direct inputs of energy to intensive systems are high in relative terms. This pattern of emissions is worrying for agriculture as it is extremely difficult to reduce emission from farms by reducing fossil fuels and, under current inventory rules, reductions in the use of fossil fuels are not credited within the agriculture inventory [33]. However further work is needed to more fully explore the impacts of possible mitigation activities on GHG emissions balances. This could also aid knowledge exchange to promote the uptake of renewable energy technologies and integrated business solutions, developing low carbon footprint technologies and their expansion within the Agri-Food and other commercial sectors.

4.4. Operational implications

One of the main challenges to the development and establishment of this multi-themed, renewable energy production centre, was the sheer volume of technical skills that have had to be learned. Staff attendance time (general duties) for the biomass boilers averaged 5.5 man hours per week, much higher when compared to the oil only system (<1 hour per week). This is not an uncommon feature of multi-form renewable energy projects [24]. Going from a wholly oil-based heating system with relatively low maintenance and little requirement for direct input, to dealing with five different and sometimes intensively hands-on technologies, was under-estimated in terms of staff time commitment compared to standard oil heating operations, requirements that are essential in planning renewable energy installations [11,24]. Just the familiarisation with equipment to attain a working degree of competence and learning to deal with minor problems, for instance releasing jammed feed augers, involved a learning process for staff that had no previous experience of these fuels and boilers. These sort of development issues were similar to reports in other facilities [4,24]. The maintenance and repair procedures also made a significant impact on operational efficiency, though this was a procedural system unlikely to occur in commercial installations. The complexity of the computerized control building energy management system (BEMS) was a quite demanding factor within the renewable energy system adoption process. However, the BEMS system was critical to the smooth operation of this plant, an essential requirement for multi-sourced power generation plants, particularly renewable energy [12]. Without this control system the running of this plant and local district heating system would not have operated.

4.2 Conclusions

The operational results reported in this study from a farm based combined heat and power facility, have shown that the displacement of fossil fuel and reduction of CO₂ emissions by the biomass, biogas and solar renewable energy systems, have achieved considerable financial savings and environmental benefits. That these were seen to actually continue year on year, has validated the adoption of these technologies at this particular type of medium scale farm enterprise. However, ineffective and poorly co-ordinated maintenance and repair scheduling can adversely affect system operation and energy production efficiency. Although there are other options available to reduce GHG emissions on farms, this study shows that the

generation of energy from renewable sources in the research centre to reduce energy use from fossil fuels, thereby cutting net CO₂ emissions, can be considered a positive mitigation option.

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Forbes et al, 2016. Tables and captions.

Table 1. Renewable energy technologies installed in the Hillsborough energy centre.

Output	CHP	Biogas	Woodchip	Multi-fuel	Oil	Solar	Solar
kW	unit	boiler	boiler	boiler	boiler	PV	thermal
Electricity	23	-	-	-	-	11.9	2 x 2.5
Heat	40	120	320	120	660	-	-

Table. II. Solid biomass fuels used at the AFBI energy centre between 2009 and 2014

Fuel	Production	Location	Distance	Tonnes	MC
Type	Method	Geo. data	(km)	(fresh)	(%)
SRC willow	Cut and chip harvested	54.3°N,-6.6°W	35 - 40	483	46.4 ± 7.8
SRC willow	Stem harvested	54.4°N,-6.7°W	50 - 60	634	42.2 ± 10.6
Conifer log chip	Machine harvested & chipped	Hillsborough	on-farm	494	37.6 ± 4.8
Brash	Baled & chipped	Hillsborough	on-farm	365	37.5 ± 12.3
Pre-dried willow	Cut and chip & forced air dried	54.4°N,-6.3°W	15 -35	39	16.6 ± 0.9
SRC willow	Cut and chip harvested	Hillsborough	on-farm	325	53.5 ± 8.5

MC = wood moisture content (% mass fraction) ± standard deviation (sd). Distance (km) = supplier distance.

Table II. Total yearly electricity (kWh) production from the 11.9 kW (peak) photo-voltaic system at AFBI Hillsborough

PV	2010-11	2011-12	2012-13	2013-14	2014-15
kW	4232	8387	9045.5	10110.51	10054

Table IV: Values recorded from combustion of four distinct fuel types run over four different time periods.

Fuel	Combustion	Quantity	MC	Heat	Heat	CV	CV	Ash
(type)	Periods	(Mg)	(%)	(MWh)	(MWh Mg ⁻¹)	(MWh Mg ⁻¹)	(%)	(kg Total)
Brash	27/11/08 - 05/02/09	45.9	17.3	140.7	3.1	4.3	71.3	600
SRC willow (std)	06/02/09 - 17/04/09	58.0	12.3	16.8	2.9	4.6	65.2	660
Mixture	07/02/14 - 09/03/14	59.3	30.0	153.8	2.6	3.5	74.1	215
SRC willow (rh)	10/03/14 - 29/04/14	71.5	26.1	185.6	2.6	3.8	68.3	920

Brash- conifer clear-fell logging residues: SRC Willow (Std)- cut and chip harvested: Mixture- 80% conifer (whole tree) with 20% willow (stem): SRC willow (rh)- whole rod harvested and open air stored for 6 months then chipped.

CV- realizable calorific values for wood at a given moisture content, source; Biomass Energy Centre (BEC) U.K. [15].

CV (%) - actual percentage of energy output of BEC nominal value.

Table V. Total and yearly heat (MWh) produced from each source at the farm energy centre between 2009 and 2014

Fuel type	09-10	10-11	11-12	12-13	13-14	Total MWh 5 y ⁻¹
Oil	91.1	406.9	73.5	224.3	167.1	962.9
Woodchip	561.2	678.3	721.7	729.0	937.3	3627.5
Multi-fuel	175.5	237.9	199.9	9.5	102.5	752.3
Biogas	128.6	158.6	292.4	498.5	278.2	1365.3
CHP	161.8	248.1	288.5	234.8	108.8	1042.0
Solar	5.6	8.4	8.2	6.4	7.7	36.3
Total MWh y ⁻¹	1123.8	1738.2	1548.2	1702.4	1601.7	7750
Total minus oil	1032.7	1131.3	1501.7	1478.1	1434.6	6787

Figures (Revised) for BBJ . Forbes *et al.* 3rd March 2016.

Figure 1. (copy from slide)

Figure1I- Metafile version

Figure 2. Windows metafile (Schematic and legend)

Figure 3- colour

Figure 3- black & white

Figure 4- colour

Figure 4- black & white

Figure 5- colour

Figure 4- black & white

Figure 6. colour

Figure 6- Black & white

Figure 7- colour

Figure 7- black & white

Figure 8- colour

Figure 8- Black & white

Figure 9

Figure 9. Black & white

Figure 10- colour

Figure 10- black & white

Figure 11. Colour

Figure 11. Black & white

End.

Captions for; Forbes *et al* 2016.

Figure 1: Schematic of the environment and renewable energy centre (EREC) at AFBI Hillsborough

Figure 2: Integrated renewable energy scheme at AFBI Hillsborough, Northern Ireland.

Figure 3: Yearly electrical output (MWh) from the 23 kW biogas CHP unit (error bars = *sd* monthly output)

Figure 4: Monthly PV electrical production (kWh) displayed for each year of operation.

Figure 5: Yearly heat (MWh) production from the biogas fuelled CHP unit and biogas boiler (error bars = *sd* monthly output)

Figure 6: Yearly heat productivity (MWh) from the woodchip and multi-fuel boilers (error bars = *sd* monthly output)

Figure 7: Annual accrual of heat (MWh) from solar thermal units and changes (% mass) in oil use. (error bars = *sd* monthly output)

Figure 8: Reductions in energy costs and carbon (CO_{2e}) emissions from AFBI Hillsborough since the introduction of renewable energy heat and power technologies.

Figure 9: Electricity use and associated GHG emissions from base year (2008) (reduction from 2008 due to electricity generation from the anaerobic digester and solar technologies at AFBI Hillsborough).

Figure 10: Yearly electricity consumption at the AFBI farm estate and electricity production from the energy centre (error bars = *sd* between years)

Figure 11: Heat source contributions as percentages of the total heat outputs at the AFBI Hillsborough energy centre (error bars = *sd* monthly output).

END.