BIONATURE 2012

The Third International Conference on Bioenvironment, Biodiversity and Renewable Energies

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Foreword

The Third International Conference on Bioenvironment, Biodiversity and Renewable Energies (BIONATURE 2012), held between March 25-30, 2012 - St. Maarten, Netherlands Antilles, covered these three main areas: environment, biodiversity and invasion, and renewable and sustainable energies.

Environmental change awareness is a key state of spirit and legislation for preventing, protecting, and ultimately saving the planet biodiversity. Technical and practical methods for applying bio-agriculture for the public's health and safety are primary targets. The goal is the use of ecological economic stimuli in tandem with social and governmental actions preventing deforestation, pollution, and global warming. To cope with the climate and landscape changes advanced technical inventory of tools and statistics on lessons learned are needed to derive appropriate measure and plan accordingly.

The biologic equilibrium on its vast immensity is a challenge for both knowledge gathering and its understanding. Preserving the existing species under rapid economy, one the one side, and using the diversity of environmental species for industrial purposes is a very week balance. There is a risk of forever damaging the existence of thousands of species, or miss the opportunity of using them for the benefit of humanity. Therefore, measuring and interpreting the impact of human actions on the diversity on marine and oceanic life, on Arctic and Antarctic bio-climate, or on forest ecosystems represent one way to prevent ecological disasters and predict possible environmental changes. The event deals with such ecosystem diversity, and the use of their existence for humanity in terms of industrial products, drug production, but also in terms of studying and modeling the ecological degradation, such loss of Poles' ice, food-chain dependency survival, wildlife endurance, or ozone holes. It also bring to the stage different disruption side-effect of the landscape changes, detection and warning systems, invasion of alien species, and the need for public awareness and education.

Replacing the classical energy with alternative renewable energy (green energy), such as bioenergy, eolian energy, or solar energy is an ecological and economic trend that suggests important socio-economic advantages: using native renewable resources, increasing of self-sufficiency rate of energy and promoting use of clean energy, and that way, polluting emissions to the air will be reduced. Bioenergy is renewable energy derived from biological sources, to be used for heat, electricity, or vehicle fuel. Biofuel derived from plant materials is among the most rapidly growing renewable energy technologies. In several countries corn-based ethanol is currently the largest source of biofuel as a gasoline substitute or additive. Recent energy legislation mandates further growth of both corn-based and advanced biofuels from other sources. Growing biofuel demand has implications for U.S. and world agriculture. Eolian energy is currently used throughout the world on a large scale. In the past decade, its evolution shows its acceptance as a source of generation, with expressive growth trends in the energy matrices in the countries where this source is used Eolian energy is renewable and has very low environmental impact. To generate it, there are no gas emissions, no effluent refuse, and no other natural resources, such as water, are consumed. Photovoltaic technology makes use of the energy in the sun, and it has little impact on the environment. Photovoltaics can be used in a wide range of products, from small consumer items to large commercial solar electric systems. The event brought together the challenging technical and regulation aspects for supporting and producing renewable energy with less or no impact on the ecosystems. There are several technical integration barriers and steps for social adoption and governmental legislation to favor and encourage this kind of energy.

We welcomed technical papers presenting research and practical results, position papers addressing the pros and cons of specific proposals, such as those being discussed in the standard forums or in industry consortia, survey papers addressing the key problems and solutions on any of the above topics short papers on work in progress, and panel proposals.

We take here the opportunity to warmly thank all the members of the BIONATURE 2012 technical program committee as well as the numerous reviewers. The creation of such a broad and high quality conference program would not have been possible without their involvement. We also kindly thank all the authors that dedicated much of their time and efforts to contribute to BIONATURE 2012. We truly believe that, thanks to all these efforts, the final conference program consisted of top quality contributions.

We hope that BIONATURE 2012 was a successful international forum for the exchange of ideas and results between academia and industry and to promote further progress in bioenvironment, biodiversity, and renewable energies.

We are certain that the participants found the event useful and communications very open. The beautiful places of St. Maarten surely provided a pleasant environment during the conference and we hope you had a chance to visit the surroundings.

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Life Cycle Assessment of the Microalgae Biofuel Value Chain

A critical review of existing studies

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***Abstract*—Innovation towards a scalable and viable microalgae industry for renewable and sustainable bioenergy is greatly assisted by the application of life cycle assessment as a benchmarking tool to guide the process. This work examines existing studies in the field that have attempted to assess either the environmental impact and/or commercial viability of the microalgae value chain. Existing literature tends to omit established conventions of life cycle assessment practice, and/or lacks a common approach to boundary definition, functional units and impact assessment that would enable more effective comparison of options. A move towards a 'level playing field' methodology would enable strategic prioritization of research efforts to emerge that could lead to more rapid development of preferred products, cultivation and harvesting technologies, and downstream processing pathways.**

Keywords: microalgae, life cycle assessment, life cycle impact assessment, value chain, techno-economic assessment

I. Introduction

Life cycle assessment (LCA) is a tool within the broad discipline of life cycle management (LCM), "a business management approach that can be used by all types of businesses (and other organizations) to improve their products and thus the sustainability performance of their companies and associated value chains" [1]. LCA is commonly used as a means to benchmark and compare designs, processes and systems, with a view to continuous improvement. Based on standardized methods published by the International Standards Organization (ISO 14040/14044 [2006]), it can provide valuable insight into the overall efficiency and impact of discrete energy and material flows that are relevant to processing and manufacture of a product across its various life cycle stages, and for assessing the aggregated impact of these as a whole.

The benefits of conducting LCA include the ability to;

1. identify and hone in on environmental and economic risks or 'hotspots' within a products' life cycle.
2. gain an understanding of both the upstream and downstream implications of various design choices.
3. inform and guide decision-making as part of an innovation program.
4. communicate more effectively and credibly regarding environmental claims.
5. benchmark, report and track on progress over time.
6. apply a common life cycle impact assessment (LCIA) method to effectively compare the overall product, system or process 'footprint' with its relevant alternatives.

A common criticism of LCA studies based on the last point above, including those relating to biofuels, is that they often have no collective basis for real comparison of results and are not based on a shared set of assumptions or assessment methods [2, 3]. As such, LCAs are sometimes criticized of being manipulated to justify environmental claims, or to retrospectively produce favorable or biased results of products. Likewise, many published LCA studies often present little more than an energy and greenhouse gas (GHG) audit, or life cycle inventory (LCI) only, with no impact assessment methodology applied at all. As such, the relative impact of various identified or documented flows of energy or materials at a macro-scale can be either absent, obscured or misrepresented, even where large flows for instance may be immaterial to the overall outcome (or vice-versa).

While this paper presents a selection of published LCA studies relating to microalgae biofuels, it is not the intention of this review to query specific numbers or findings, as such, or to comment on the veracity of results. However, the purpose of reviewing existing studies is to underscore how differences in LCA methodology make it difficult to achieve collective progress towards commercialization of the microalgae biomass value chain in the absence of shared methods for framing of studies and presentation of relevant data, including assessment of environmental impact. As such, the purpose of this investigation is to highlight the many variables inherent across the life cycle, from species selection through to processing and delivery of downstream products, with a view to recommending a more strategic, industry-wide collaborative approach to LCA-driven innovation, based on agreed standards.

The structure of this paper is based firstly on presentation and discussion of the US DOE's microalgae biofuels industry roadmap, followed by a review of existing LCA studies, focus on the various methodological orientations

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taken, discussion of co-products and allocation in LCA, and finally, conclusions and future work.

II. Methodological Challenges in Microalgae LCAs

The following section outlines the industry roadmap and describes the many differences that exist between published studies, research pathways and areas of commercial endeavor that influence LCA modeling and interpretation.

A. Prospects for a common approach

The US Department of Energy published a *National Algal Biofuels Technology Roadmap* under the auspices of the Biomass Program in May 2010 [4]. This document sets out the broad parameters within which techno-economic assessment and innovation of the algae biofuel product value chain can and should occur, in order to drive towards full commercialization. It advocates the integration of recognized LCA methods, with a specific focus on leveraging previous biofuel feedstock studies.

Additional aspects considered in the DOE report include the opportunity to leverage GIS technology to identify specific areas suitable for scalable microalgae cultivation, based on availability of non-arable land and proximity to necessary process inputs, infrastructure and markets. The report also reflects on co-location with synergistic industries, such as stationary power generators or wastewater treatment plants, as a means to explore innovation in the sector.

The DOE roadmap provides a conceptual framework that highlights the importance of LCA as tool that can contribute to commercialization efforts. Notably, the report also observes that in addition to measuring net greenhouse gas (GHG) emissions, LCA "can also assess impacts and tradeoffs associated with utilization intensity for water, energy, nutrients, and other resources." [4]

Overall, the roadmap presents a critical challenge for LCA, namely that there are multiple cultivation and processing choices that can be made, spanning from species selection, through to cultivation, intermediate constituents, conversion processes and end user products and markets. The inference being that without at least some degree of harmonization of data collection, boundary definition and/or assessment methods, effective comparison, prioritization and innovation across multiple pathways will be extremely difficult.

B. Review of existing studies

The existing published works reviewed here are related to microalgae LCA and are divided into three broad categories. The first covers the spectrum from energy, greenhouse gas and mass balance calculations, to high-level 'scoping' LCA studies [5-7]. These do not report beyond a limited set of metrics and/or do not appear to apply or present any discrete LCIA method.

The second category of studies appear to be based on more traditional LCA reporting practices that take a more comprehensive approach to LCIA [8-11]. Nevertheless, they do not generally share a common set of goals, system boundaries, assumptions and/or impact assessment methods, and only the overall approach and structure each adopts is similar, at the very highest level (as proscribed by the ISO standard).

The final category sees LCA results and 'life cycle thinking' either directly or indirectly implicated through techno-economic assessments (TEAs), that seek to primarily address the commercial feasibility of the process overall [12, 13]. These may or may not include an approach designed to also measure, assess and report on environmental impacts, however their consideration is necessary to appreciate the growing body of work in this area. While a TEA is a fundamentally different proposition to an LCA, it must be based on relevant assumptions of productivity, as well as material and energy flows, that enable a fully costed model to be assembled. As such they do share common data elements with LCA, although the approach to data collection, interpretation and validation may well be quite different.

Since microalgae is posited as a sustainable alternative to fossil sources of material and energy, those concerned primarily with assessing the environmental impact of industrial microalgae production seek at a minimum to ensure that the overall value chain leads to a net carbon reduction [14-16]. Those interested in techno-economic studies seek, in the main, to establish the capital and/or operating cost profile of an end-to-end process, to ensure economic viability of the proposition. Ultimately, integrated assessment from both perspectives is necessary in order to realize the goal of a scalable, ecologically sound, socially responsible and yet commercially viable solution, surely the intent of sustainable development [15, 17-20].

However, reducing capital and operational costs and adequately assessing environmental impact is complex as fully scaled commercial operations are essentially non-existent and lab scale findings must often be relied upon for extrapolation [10]. Cultivation and harvesting technologies for instance are mostly immature and yet to be realized, hence many studies represent, "a prospective LCA of a non existing process" [8], and very few published studies have even gone on to consider human resource demands of operation, such as labor implications [21].

One study seeks to overcome the nascent status of a scaled microalgae industry by suggesting a bulk growth model that will enable more accurate LCA studies to be formulated [22]. This uses a series of mathematical models relating to light intensity, nutrient uptake and lipid accumulation for instance, to predict maximum thresholds of productivity, also applying a sensitivity analysis to develop a level of confidence in results. The approach put forward also makes allowance for differing geographic locations, since this impacts directly on growth and is a key aspect often overlooked in existing microalgae LCA studies. Comparability of algae LCA studies also depends greatly on consideration of a common species, since a biochemical profile is fundamental to achieving productivity goals and downstream refinement into desired end products [23].

TABLE I. COMPARISON OF MICROALGAE LCA SYSTEM STUDIES

Study	Features of the study			
	Goal & Scope/ Product Orientation	***System Boundaries***	***Functional Unit***	***LCIA/ Reporting Method***
Batan et. al. [5]	Net energy ratio & GHG of PBR grown *N. salina* biodiesel + co-products	Cultivation-to-consumer; "Strain-to-pump" cf. "well-to-wheel"	Temporal, based on production process over 1 year	GREET 1.8c; displacement of co-products applied
Campbell et. al. [24]	GHG balance of *D. tertiolecta* in open ponds cf. ULS diesel + economic costs; includes people	Pond vs. well-to-tailpipe	CO_2e- of GHG emissions/t /km in an articulated truck	UNFCCC GWPs of GHGs only (100yr)
Chisti [13]	GHG ratio of 1.83:1, based on *P. tricornutum* PBR for elect. & biodiesel cf. bioethanol; incl. economic costs	Cultivation to oil extraction + power generation	MJ/t algal biomass	GHG balance only
Collet et. al. [8]	Biogas production cf. biodiesel from *C. vulgaris* grown in open ponds	Cultivation-to-generator gate; includes 30yrs fixed infrastructure	1 MJ fuel combusted in a gas engine	CML; substitution of co-products applied
Clarens et. al. [14]	Producing energy from algae biomass vs. corn, canola and switchgrass	Cultivation-to-processing gate (delivery of biomass)	317 GJ of biomass-derived energy	Crystal Ball; MJ, m^3 H_2O, CO_2e-, kg PO_4- eq., Ha land
Jorquera et. al. [25]	Net Energy ratio (NER) of *Nannochloropsis* sp. grown in multiple growth systems	Cultivation-to-processing gate (delivery of biomass)	1kt of dry weight	NER only
Lardon et. al. [10]	Expanded boundaries to ascertain broad impact of *C. vulgaris* biodiesel in open ponds cf. diesel	Cradle-to-combustion (fuel), Cradle-to-grave (facility); includes 30yrs fixed infrastructure	1 MJ fuel combusted in a diesel engine	Partial CML: AbD, Ac, Eu, GWP, Ozone, HumTox, MarTox, Land, Rad & Photo
Pfromm et. al. [6]	Mass balance orientation based on chemical engineering tehcniques, held as distinct from LCA 'accounting'	Uses conservation of mass, hence cradle-to-grave, incl. the atmosphere	LHV equivalent of 50m gal of petro-diesel	Balance calculation only - electrical energy, thermal energy, fertilizer, CO_2
Sander & Murthy [26]	Benchmarking algae biodiesel against other transport fuels, highlighting sustainability concerns	Cultivation-to-consumer; ("well-to-pump"), 5% cut-off value	1,000 MJ of energy	Relative mass, energy and economic (RMEE)
Soratana & Landis [11]	Biodiesel from *C. vulgaris* grown in a PBR, using 3 parameters: PBR material, source of CO_2, source of nutrients	Cultivation-to-pump; temporal also (5,10, 20yrs), includes infrastructure	3650kg of algae, grown over 20yrs	TRACI 3.01
Yang et. al. [7]	Water footprint of open pond culturing of *C. vulgaris*	Cultivation-to-finished product	1kg biodiesel	Water & nutrient balance

Critical differences between LCA and TEA studies create challenges in constructing an integrated picture since they each have slightly different conventions and overall orientation. In an LCA, it is common to specifically *exclude* the impact of fixed assets and infrastructure, since experience has shown that it is the environmental impacts related to the operational phase of a product value chain or process that dwarf all else. On the other hand, a financial assessment seeks to encompass all assets and operational costs (including labor), as accurate capital and operating projections are fundamental to building a business case, raising project finance and to calculating tax benefits such as depreciation. In this way, the veracity of LCA data is often far less 'complete' in terms of the precision of actual numbers than the 'line-by-line' accounting approach taken by a TEA. Nevertheless, sensitivity analysis, coupled with LCIA, can reveal credible scientific insights based on LCI results, without the need for absolute certainty on the volume of individual flows, especially where their variance is found to be inconsequential to the final result.

The existing body of work designed to assess the industrial-scale microalgae prospect also seeks to compare and contrast findings from a diverse number of analytical viewpoints (Table 1). For instance, some reports use the intermediary or end products (e.g. FAME, carbon abatement, MJ equivalent) as the basis of comparison [5], whereas others use the cultivation system [13], or perhaps both [27]. There are several trade-offs to be considered in design of the entire system, though it can be generalized that the greater amount spent on capital equipment and infrastructure (such as comparing open pond systems with photobioreactors), the higher the biomass productivity per unit area that can be expected [14, 15, 17, 28, 29]. Hence, a key position many studies attempt to establish is the point at which this trade-off is no longer justified.

A comparison of select studies, further highlighting the fundamental differences in approach to system boundary definition, is presented in Figure 1. All of these positions are equally valid however contribute to general confusion regarding system boundaries, goals, functional units, impact reporting categories and/or methods that would otherwise make fair and transparent, 'level playing field' comparison of value chain options across the innovation landscape possible [5].

C. Functional units, comparability, inclusions and exclusions

A study comparing the life cycle impact of cultivating microalgae in open ponds versus photo bioreactors (PBR) proposes a focus on net energy ratio (NER) as a functional unit, wherein the construction process and materials used, in addition to process energy, are collectively taken into account when making inferences about their relative suitability and efficiency [28]. However, the environmental impact of their respective operational lives, in this case mostly related to the energy used in pumping, mixing and CO_2 delivery, as well as possible impacts associated with process nutrients, will far outweigh these calculations relating to infrastructure [9], hence this metric appears questionable.

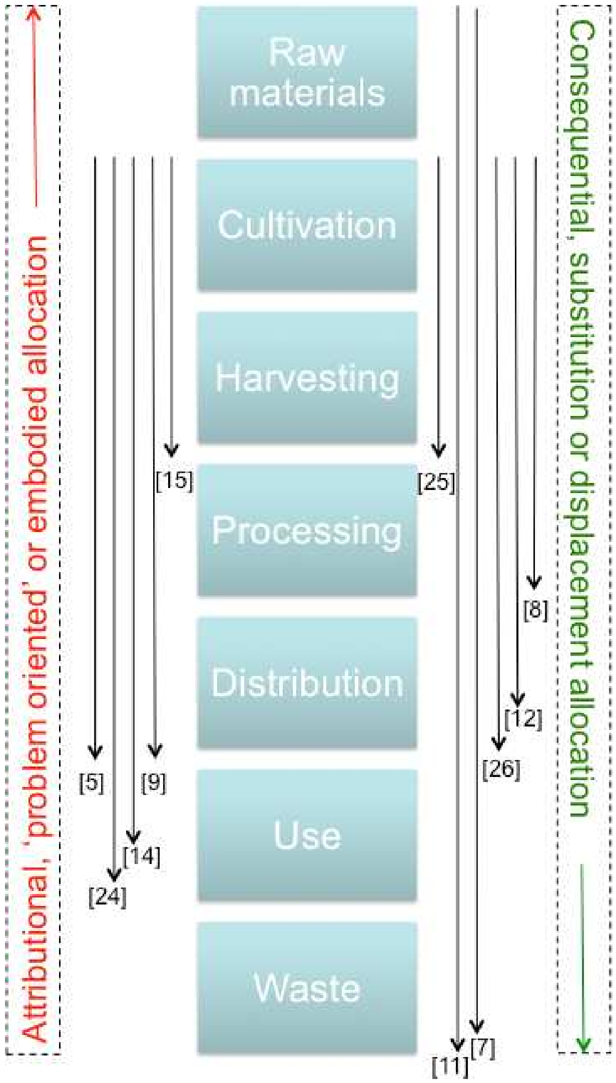

Figure 1. Examples of contrasting system boundary definitions in microalgae biofuel LCAs and related system studies (ref. Table 1)

Another illustrative work targets LCA of algae biodiesel, suggesting through this analytical approach that for every 1kg of algal biodiesel produced, approximately 1.4kg of co-products are generated [26]. This study is notable for several reasons. Firstly, it adopts the RMEE method wherein data relating to specific unit processes is assembled prior to the selection of system boundaries with the intent of avoiding arbitrary exclusion of certain items. The functional unit chosen relates to 1000 MJ of energy, based on a 'well-to-pump' system boundary. Mass, energy and economic value ratios are calculated for each input, with a cut-off ratio of 5% chosen as the sole basis to exclude items. This has the effect of neglecting the imbalance that often exists in relation to the type and volume of certain flows and applying a sensitivity filter *before* any impact characterization is undertaken carries this risk. That is, the environmental impact of certain industrial chemicals for instance are often disproportionate to the volume of their flows, hence this LCA approach could overlook such inventory items that would otherwise be captured under the terms of a more comprehensive study.

Another 'problem oriented' study coupled wastewater treatment and high rate algae ponds together to solve both an environmental and commercial problem. This is proposed as an example of the means to close the competitive price gap between the cost of biofuel production and incumbent fossil fuels [30]. In addition to removing nutrient from the water (a useful process input for algae growth), the capital and operating cost of a conventional wastewater treatment plant can be redirected to algae ponds and process water is better utilized overall.

Of particular relevance to realizing full-scale commercialization of algae biomass, biofuels and bioproducts is the establishment of a 'level playing field' approach to synthesis and interpretation of LCI results, that enable them to be interpreted in a meaningful way. This is essential in order for such studies to be comparable across the industry itself, regardless of the desired output product/s [31].

A comparative study of microalgae systems modeled 20 different cultivation scenarios, with a view to evaluation of 3 key parameters, namely chosen material for PBR construction, source of nutrients and source of CO_2 [11]. A further temporal dimension was added to this analysis to view the impacts of various scenarios in terms of length of operation of 3 alternate timescales. The LCIA method used here was based on the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI), from which 9 impact reporting categories were selected and reported against. The functional unit in this case benchmarks all LCIA results against the ability of a standardized PBR design to deliver a calculated yield of algae biomass over time (essentially based on productivity potential), with a view to downstream conversion to biodiesel. The standardization of reactor design in this work provides a useful anchor point, and leads to the observation that choice of PBR materials has a significant impact in relation to several environmental metrics, where this capital infrastructure is included in the model.

Production of algal biodiesel is assessed in a UK-based study, wherein the avoided impacts, or 'reference systems' are also modeled in order to establish the quantum of benefit [32]. LCIA is based here on a recognized, consistent reporting method, EDIP 2003, which adds gravitas and a degree of comparability to the results. In the case of liquid fuel substitutes, extending system boundaries to include combustion is necessary given that in this case, algal biofuel properties will differ when compared directly with their fossil alternatives [10, 29].

D. *Co-products and the challenge of impact allocation*

Since microalgae systems present an opportunity to remediate wastewater streams, address the emissions intensity of stationary power generators and heavy industry, as well as offset fossil resource consumption, this prospect offers potential environmental advantages when considered from an attributional LCA perspective, albeit from one that addresses multiple problems simultaneously [14]. This has important and possibly controversial implications for allocation of environmental impacts and suggests that more of a 'consequential' LCA orientation would neatly sidestep the inherited burden of the upstream processes (such as coal-fired power) that feed into it.

Attributional LCA by definition only really assists with answering a question based on the environmental impact of a burden at any given moment in time, largely based on average production practices. This is useful for simplified benchmarking and certification of environmental performance however fails to recognize the positive flow-on effects that a value-adding solution such as microalgae might deliver over time. Consequential LCA takes on a much larger scope by effectively trying to model scenarios over decades, including coupled flow-on effects and marginal changes, however adds significant additional complexity to the process.

Some published algae LCA studies that take an attributional approach conclude that algal biofuels are likely to perform poorly when compared with terrestrial biofuels from an environmental perspective. This is mainly reflected in the results for CO_2 and nutrients, hence the clear preference towards wastewater and emissions intensive-coupled growth systems as drivers of industrial microalgae commercialization [14, 16, 33]. Further, since water is also identified as a critical limiting factor for many potential algae cultivation sites, exploitation of wastewater for growth of freshwater algae species is likely to be essential to achieve any significant scale of production [34].

A thoughtful discussion of allocation methods in a study of algal biodiesel suggests direct substitution (consequential allocation) as the preferred approach, before concluding that byproducts and their impacts (where they only substitute existing waste byproducts of other processes, such as heat) should be avoided [32]. The reflection is that economic allocation is the simplest and best method to apply, in this case an approach to LCA that is in line with the demand cycles of the open market, albeit perhaps in conflict with the more optimistic, future-oriented view that a consequential orientation would deliver, in terms of assessing long terms impacts related to sustainable development.

Of critical interest to allocation in the microalgae context is the extent to which the downstream cultivation of microalgae (where CO_2 from an adjacent power station is utilized for growth) is considered an inherited environmental burden to the overall process. An undesirable outcome may result through application of an attributional LCA method, where burden is passed on and distributed proportionately down a value chain, whereas a consequential approach may lead to a more favourable assessment over time.

III. Conclusion and Future Work

It is clear that LCA can be a valuable tool for innovating across the microalgae value chain with a view to full commercialization. However, there needs to be greater methodological consistency between LCA studies to guide this effort. In the case of algal biomass, allocation is a key methodological issue that needs to be strictly consistent in relation to assessment of all technologies and pathways, as this enables more balanced decision making to be made based on both utilization of wastes and generation of co-products. Future work should address the issue of harmonization of agreed system boundaries and LCIA methods, collectively benefitting the industry and enabling it to benchmark and report on multiple value chain options with greater confidence and comparability, based on a 'level playing field' approach. This effort should draw on the experience of other industries in establishing a common approach, in particular those that have already developed such LCA-driven methods, such as the Building Products Innovation Council (Australia) and The Sustainability Consortium for benchmarking of consumer products.

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System Approach to Biomass Pyrolysis: Product Characterisation

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***Abstract*— Engineering a system solution of the biomass pyrolysis process requires thorough investigation of the possible end-use applications of the biomass pyrolysis products (bio-oils and bio-char) in order to determine the most feasible and greenhouse gas abating options for their use. This work investigates the biomass pyrolysis process of three potentially applicable energy crop species and provides characterization of the biooil and biochar products of pyrolysis. The analysis suggests that the biochar contains the OH, aromatic C=C and inorganic Si-O-Si bonds. The biooil samples exhibited much more complex structure and were highly variable in composition suggesting requirement for their further upgrading.**

Keywords-biomass, pyrolysis, biofuels, biogas, biooils

I. INTRODUCTION

A renewed interest in biomass as an alternative energy source is apparent in both developing and industrialised countries, primarily because of its renewable character and potential for reducing net atmospheric CO_2 emissions when substituted for fossil fuels. Biomass is the generic term for materials derived from plants or animal manure. According to McKendry [1], biomass materials can be classified in four categories: woody plants, herbaceous plants or grasses, aquatic plants and manures. On average, woody biomass contains about 50 wt% carbon, 43 wt% oxygen, 6 wt% hydrogen and the remaining 1 wt% is nitrogen [2] with the average mean formula expressed as $CH_{1.44}O_{0.66}$ [3].

When biomass is harvested and processed in a sustainable way, biomass to energy conversion has zero net atmospheric CO_2 contribution because the carbon emission from biomass utilisation equals the photosynthetic atmospheric carbon fixed during the lifetime of the plant. The potential climate risk caused by excessive CO_2 emissions from fossil fuel utilisation is cited as the main driver for accelerated developments in renewable based energy generation, with biomass energy generation being one of the most prospective among all renewable energy sources. Biomass use as a fossil fuel replacement has a particular advantage as it can fractionally replace the fossil fuels in existing energy generation technologies without requirement for large and capital intensive engineering adjustments.

The share of energy generation from various biomass sources is estimated as; 64% from wood, 24% from solid wastes, 5% from agricultural wastes and 5% from landfill gases [4]. The main industries producing biomass wastes are the timber, sugar, cotton, agricultural and food industries. According to the National Renewable Energy Laboratories, the world produces biomass equivalent to 2893 EJ annually. The International Energy Administration estimated that in 1995 the world consumption of biomass was in the order of 343.6 EJ, which is less than 12% of the total production capacity. The developed world still associates biomass with waste and most of the biomass in some countries is destroyed through field burning or disposed in landfills [5]. As an example, in the Sydney region alone 350 Kt/a of wood waste is disposed of to landfill, which is equivalent to one million cubic metres of landfill space [6]. The current disposal practices cause additional environmental concerns as not only do they require energy to maintain the disposal sites but also the biomass undergoes anaerobic decomposition in the landfills producing fugitive CH_4 emissions, which are far more potent than CO_2. Alternatively, field burning produces CO_2 emissions, while the potential energy recovery is wasted. It is therefore more than apparent that biomass disposal requires integration into the current energy technology systems to improve efficiency and sustainability.

A significant advantage of the use of biomass materials is that they are renewable sources and can be purposely grown for energy use. They are generally low in sulphur and nitrogen, hence biomass energy conversion potentially results in lower SO_2 and fuel-NO_x emissions comparing to fossil fuel based energy generation [7]. These materials can be managed more effectively due to the generally lower composition of toxic trace metals when compared to coals [8]. A significant constraint to increased biomass utilisation is its low density which results in higher volume to mass ratios during transportation and storage. Also, most of the biomass materials have high moisture content. Given that the major agricultural and other biomass producing sites are located some distance from the energy utilisation plants, biomass transportation cost can be high because not only are they less dense but will also include transportation of the water. Prior processing and drying may provide a solution, however, biomass should also be handled and stored in a dried environment due to the hydroscopic ability to quickly absorb atmospheric moisture

One of the potential for increasing the net energy capacity of the biomass materials is to thermally upgrade biomass to higher calorific value fuels. Pyrolysis is one method where biomass materials are heated and decomposed under inert atmospheric conditions converting them to gaseous and liquid products and creating a carbon rich charcoal residue. All of the products of biomass pyrolysis have significant energy value and can be combusted directly to produce energy or they can find other uses. For instance, bio-oils can be further upgraded with catalytic hydrothermal processing [9] to produce bio-diesel, or they can be used as base materials to produce highly marketable chemicals [10]. Bio-char has traditionally been used as metallurgical fuel in ironmaking [11], but recently attracted significant attention as a fertiliser replacement to create highly fertile soils, while at the same time biologically sequestering atmospheric carbon [12].

Pyrolytic processing has been identified in the literature as one of the feasible technologies available to thermally upgrade biomass materials to higher calorific value fuels [13]. Most of the studies to date have been focused on adjusting pyrolysis parameters to achieve maximised bio-oil or bio-char yields. There is significant lack of a systems approach to the biomass upgrading process, an approach which would integrate the pyrolysis conditions, with the upgrading potential of bio-oils to produce bio-diesel and petrochemicals, bio-gas utilisation and bio-char application either as fertilising material or metallurgical fuel, as well as bio-carbon sequestration. A systems approach to the pyrolysis of biomass will not only enhance competitiveness of the higher calorific value renewable fuels and petrochemicals, but will also promote sequestration of atmospheric greenhouse gases.

Fig. 1 details the opportunities for energy and material recovery from biomass where biomass drying and pyrolysis are self driven and maintained through combustion of the produced bio-gas and/or bio-oils. The final pyrolysis products can have various end-of-stream applications, each one offering different advantages and disadvantages. The most feasible stream would be selected by a comprehensive life cycle analysis taking into account the energy balance, material flows and net greenhouse gas savings.

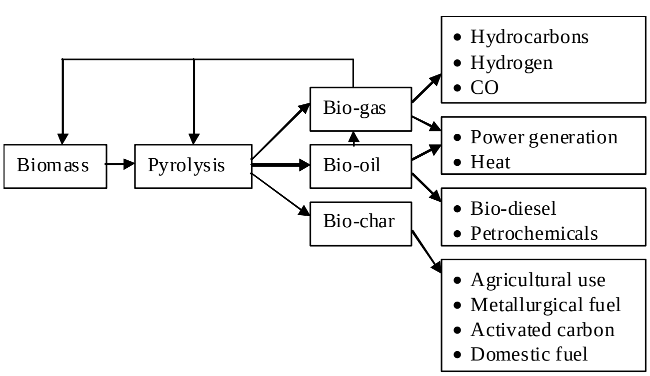

Figure 1. Pyrolysis cycle and options for energy and resource recovery from biomass.

The aim of this paper is to investigate the pyrolysis behaviour of selected biomass species and to characterize the bio-oil and bio-char products of pyrolysis which is essential to model a system approach to biomass pyrolysis.

II. EXPERIMENTAL

A. Samples

Table I shows the properties of the biomass samples used for this study. They are three typical Australian plant species which have potential to be subjected to cultivation as energy crops because of their fast growth rates.

TABLE I. PROXIMATE AND ULTIMATE ANALYSIS OF THE SAMPLES

Sample	Proximate Analysis (air dried)			
	Moisture %	*Ash %*	*Volatile Matter %*	*Fixed Carbon %*
Sugar cane	7.9	6.9	70.6	14.4
Hemp	8.3	4.6	68.7	18.4
Wattle	7.0	2.8	68.2	22.0
	Ultimate Analysis (air dried)			
	Carbon %	*Hydrogen %*	*Nitrogen %*	*Sulphur %*
Sugar cane	42.2	5.22	0.56	0.13
Hemp	41.8	5.31	1.31	0.14
Wattle	49.6	5.66	2.82	0.16

B. Experimental techniques

The samples were first subjected to Computer Aided Thermal Analysis to quantify specific and latent heat of the samples during pyrolysis. The technique has been previously detailed by Strezov et al. [14].

A Mettler Toledo thermogravimetric analyzer (TGA) instrument TGA/DSC 1 Stare System, operated with Stare software, was used to determine the weight loss of the samples with temperature. The sample weighing approximately 30 mg was placed in a circular Al crucible with an additional empty crucible employed as a reference. The experiment was carried out using N_2 as a carrier gas, set at a flow rate of 20 ml/min, with a heating rate of 10°C/min. The buoyancy correction for the TGA data was conducted using a blank experiment with no sample placed in either of the crucibles prior to each sample run.

Biooil and biochar samples were then produced in a fixed bed pyrolyser by heating approximately 2 grams of biomass to the temperature of 500^{o}C. The biooils were condensed at room temperature at the outlet of the pyrolyser.

The FT-IR spectra of the biomass, biooil and biochar samples were recorded in Nicolet 6700 FT-IR spectrometer applying Attenuated Total Reflectance (ATR) method with diamond crystal. The total number of scans was 32 with spectral resolution of 4 cm^{-1}.

The bio-oils condensed at room temperature were first dissolved in dichloromethane and then analysed using a Shimadzu GC-MS apparatus (Model QP2010), with a 30

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meter long SGE-BP1 column of 0.25µm diameter. Prior to commencement with GCMS experiments the instrument was auto-calibrated using perfluorotributylamine (PFTBA).

III. RESULTS

Fig. 2 shows the specific heat of the samples. The latent heats of pyrolysis were observed through the changes in specific heat with corresponding peaks and troughs. Fig. 2 shows that all of the samples exhibited endothermic heat of reaction starting at 100°C to 180°C associated with decomposition and release of the hydrated compounds. At the temperature range between 200 and 400°C the samples went through a very large endothermic reaction due to the breakdown of the hemicellulose and cellulose and in this temperature region, the major weight loss of the samples is also observed, as determined by the thermogravimetric analysis shown in Fig. 3. At temperatures above 400°C the specific heat showed minor reactions with peaks at 420 and 820°C in case of hemp and 750°C in case of wattle tree. These reactions are followed with only minor loss of weight in the samples (see Fig. 3). According to the thermogravimetric data shown in Fig. 3, at the temperature of industrial pyrolysis, which is typically around 500°C, the samples weigh 28%, 29.5% and 37.2% in case of sugar cane, hemp and wattle tree, respectively. The majority of the weight is lost as non-condensable bio-gas and condensable bio-oil products of pyrolysis.

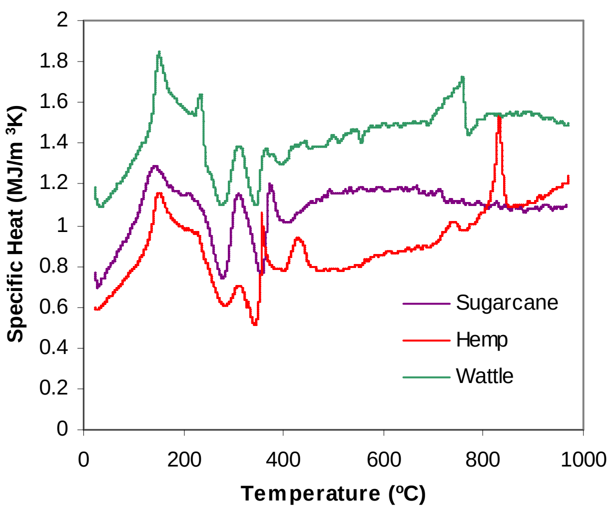

Figure 2. Specific heat of the biomass samples during pyrolysis

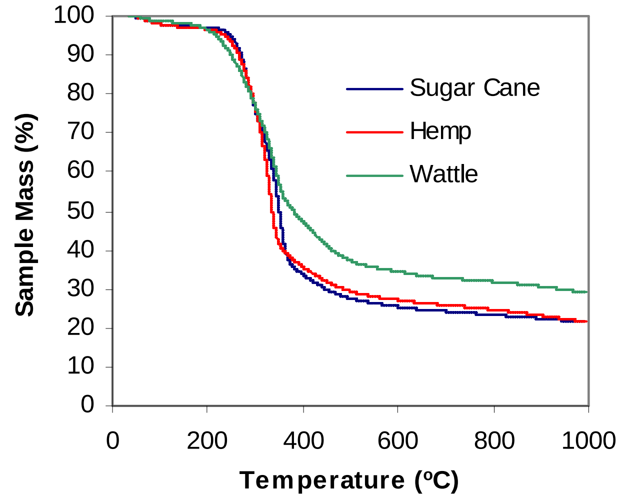

Figure 3. Thermogravimetric analysis of the biomass samples.

Fig. 4 shows FTIR spectra of the unprocessed biomass samples, the biochars produced at 500°C and bio-oils evolved at 500°C and condensed at room temperature. Interpretation of the FTIR spectra was conducted according to the guidelines outlined by Coates [15]. The raw samples all showed a very broad band with a peak at 3340 cm^{-1} due to OH stretch of the hydroxy group. The same band, although with smaller intensity was also evident in the bio-oil products of all three samples. A very minor presence of the OH groups was also monitored in the bio-chars produced from sugar cane and hemp, but not in the biochar produced from wattle tree. The double peak at 2920 and 2860 cm^{-1} observed in all biomass samples was associated with the saturated aliphatic group, in particular the methylene C-H stretch. This group was also apparent in the produced biooils, particularly showing strongest appearance in case of the biooil produced from the wattle tree sample. The raw samples also exhibited very strong peak at 1035 cm^{-1} related to Si-O-Si bond and the intensity of the peak corresponded to the ash content of each sample presented in Table I. Sugar cane, with ash content of 6.9% showed the largest intensity of this peak, followed by hemp at 4.6% and wattle tree at 2.8%. The biochars produced at 500°C also exhibited the same FTIR peak indicating that the silica from the raw biomass samples remains in the solid biochar product. The peak at 1620 cm^{-1}, most apparent in the raw wattle tree sample, was due to the aromatic C=C stretch. The same peak appeared in the biochar and to some extent in the biooil samples. The biooils also showed strong peaks at 1265 cm^{-1} associated with the phenol C-O stretch and at 734 cm^{-1} due to the aromatic C-H out of plane bend. The remaining small multiple peaks in the range between 1160 to 1520 cm^{-1} observed in all raw biomass samples and the produced biooils are likely due to the aromatic ring group frequencies.

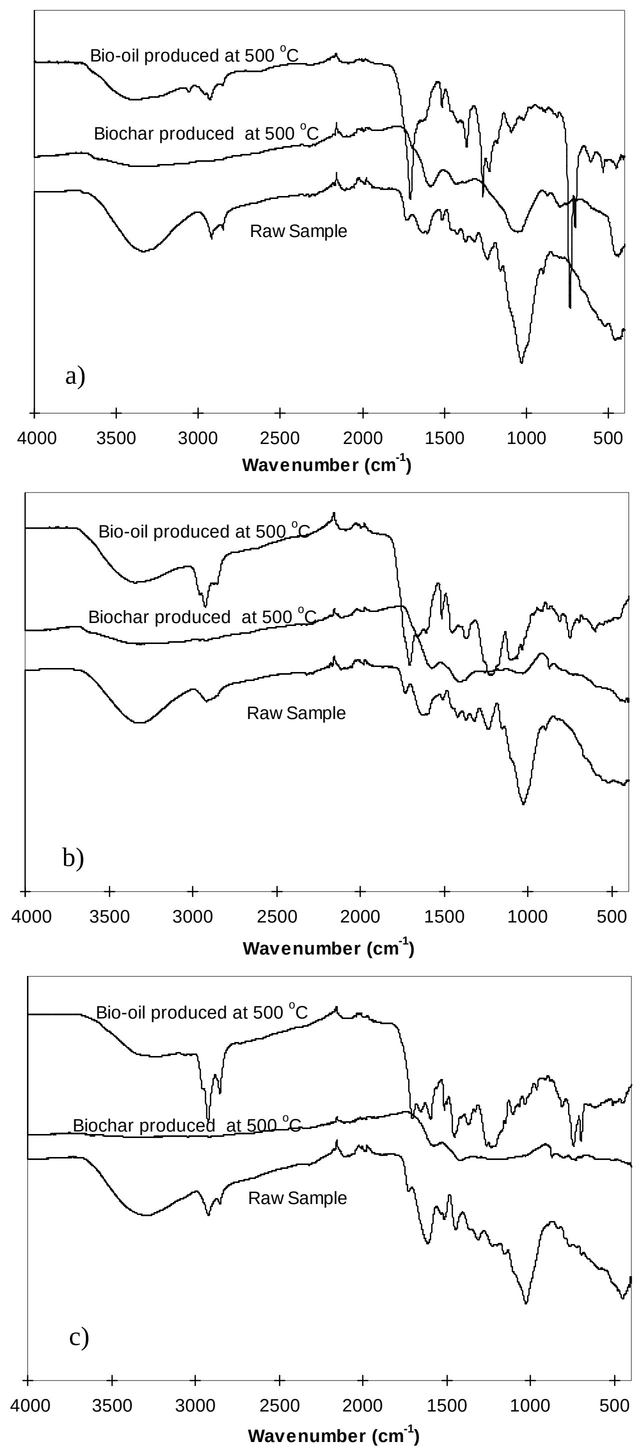

Figure 4. FTIR Analysis of the raw samples, biochars produced at 500°C and bio-oils produced at 500°C for (a) sugar cane; (b) hemp and (c) wattle tree.

The FTIR spectroscopy for analysis of biooil samples is very useful experimental technique that can be used to show how various bonds from the raw samples are redistributed to the biooil products during pyrolysis. However, for the purpose of identification of the various chemical compounds, this technique needs to be supplemented with Gas Chromatography Mass Spectroscopy (GC-MS). In this work GC-MS technique was further applied to determine the major chemical compounds present in the biooil samples and the results are displayed in Table II.

TABLE II. MAJOR COMPOUNDS OF THE PYROLYSIS OILS PRODUCED AT 500°C

Sugar cane	
Area%	Name
13.97	2-Propanone, 1-hydroxy-
4.61	Phenol
4.56	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-
4.37	Furfural
4.3	2-Propanone, 1-(acetyloxy)-
4.27	Pentanal
4.24	Phenol, 4-ethyl-
4.02	Phenol, 2-methoxy-
3.44	2-Propanone, 1-(1-methylethoxy)-
3.07	Phenol, 4-methyl-
Hemp	
Area%	Name
26.91	Acetic acid
14.8	2-Propanone, 1-hydroxy-
4.17	2-Furanmethanol
3.63	Cyclopropyl carbinol
3.29	Phenol, 2,6-dimethoxy-
2.99	2-Furanmethanol, tetrahydro-
2.77	2-Cyclopenten-1-one, 2-hydroxy-3-methyl-
2.15	Phenol, 2-methyl-
2.13	Phenol, 2-methoxy-
1.93	Nonacosane
Wattle tree	
Area%	Name
3.88	Phenol
3.38	Acetamide, N-methyl-N-(2-phenylethyl)-
3.12	Acetamide, N-(2-phenylethyl)-
3	Phenol, 4-methyl-
2.91	Phenol, 4-ethyl-
2.85	Dodecanoic acid, 2-hexen-1-yl ester
2.69	Cyclohexene, 1-octyl-
2.26	1,E-11,Z-13-Hexadecatriene
2.21	Phenol, 2-methoxy-
2.13	Acetic acid

Results shown in Table II contain the major 10 compounds detected in the biooil samples after integrating the GC-MS spectra. The results presented here show only the area of the GC-MS spectra integral with the major peak interpretation. The largest compounds detected in the pyrolysis oil sample was 1-hydroxy-2-Propanone (acetol) in case of the sugar cane pyrolysis oil, acetic acid in case of the oil produced from hemp and phenol in case of the wattle tree

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pyrolysis oil sample. Various phenol groups were also detected as some of the major compounds in all three samples. The GC-MS result indicated that the bio-oils produced from pyrolysis of the selected biomass samples are highly variable in composition and are unlikely to be suitable for direct use, except for some cases of use of pyrolysis oils as industrial fuels. For the purpose of the use as commercial fuel product, their upgrading would be essential.

IV. CONCLUSIONS

Biomass pyrolysis provides an opportunity for system solution to energy supply and biological sequestration of carbon through agricultural application of the produced biochar. The work presented here outlines some of the product characterization approaches that can be applied to perform energy, mass and life cycle assessment required to model the pyrolysis system. The results indicated that the pyrolysis process has an initial endothermic reaction followed by largely exothermic heat of reaction, which means that the overall heat requirement to complete the pyrolysis process can be partially supported by the internal exothermic reaction. The analysis of the biochar and biooil samples suggest that the biochar contains the OH, aromatic C=C and inorganic Si-O-Si bonds. The biooil samples exhibited much more complex structure and were highly variable in composition suggesting requirement for their further upgrading. Feasibility assessment should also be performed in order to maximize the opportunity of the pyrolysis as a technological solution to biomass processing.

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Strain Response of a Wind Turbine Tower as a Function of Nacelle Orientation

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***Abstract*— A land based 2.3 MW horizontal axis wind turbine steel supporting tower was instrumented with a Fiber Braggs Grating Strain array. The turbine was subjected to forced yawing of the nacelle during periods of low wind in order to isolate a baseline structural response. The strain experienced in the tower was presented as a function of yaw angle, and was shown to vary in a sinusoidal manner as a response to the eccentric loading condition present at the nacelle-tower interface. The yaw-strain baseline was shown to have strong inter-sensor cross correlation and is discussed in the context of a healthy structural response record with possible future utilization in SHM schemes.**

Keywords - Wind Energy; SHM; Strain Response; Wind Turbine Tower

I. INTRODUCTION

Due to the high initial implementation costs of wind energy, increasing the longevity of the entire turbine system is an important factor contributing to the economic viability of wind energy projects [1]. One of the main components of a horizontal axis wind turbine system is the structure's supporting tower. The towers themselves are usually constructed from steel, are assembled in multiple sections [2-4], and are commonly designed to have a lifespan of 20 to 30 years [3-4].

Figure 1: The subject wind turbine located in Southern Ontario, Canada.

Unlike most of the mechanical systems (rotors, control motors, bearings etc.) that can be replaced without dismantling major components of the system, repairing a damaged tower can be a costly procedure requiring specialty surface preparations, welding techniques and surface finishing [4]. In situations where damage is irreparable, replacing a damaged tower section involves an extraordinary amount of down time and resources to complete. In order to replace a full tower section, the entire nacelle and rotor assembly must be disassembled and subsequently re-assembled [5]. The ability to monitor and identify problems within the tower structure in a timely manner could help prevent a small tower defect from growing into a larger problem. This is commonly referred to as structural health monitoring (SHM).

Structural health monitoring has a history of implementation on large scale civil infrastructure such as bridges, dams and pipelines in order to prevent or predict catastrophic structural failure [6]. SHM has also been applied to wind turbine mechanical systems such as rotor and blade assemblies [7-9]. There has recently been interest in the literature regarding SHM of the supporting towers for wind turbines [10-11]. The basic premise of SHM techniques is that damage to a structure, such as a crack in the material, results in the changing of the structures dynamic properties (stiffness, damping, etc.). This change in physical properties results in a change in the structures' response (strain, natural frequencies, mode shape etc.) to service conditions. SHM strategies work to identify the changes in structural response in order to detect structural damage [10, 12-13]. Works examining the response of turbine towers have mostly focused on the structural dynamic response of wind turbine towers by means of finite element analysis [3, 14-18] and in-situ monitoring of wind turbine towers using accelerometers and/or strain gauges [19-21]. The main focus of these studies has been improving tower design methods.

Since many SHM schemes compare measured structural response to that of a typical undamaged or healthy structure, it is necessary to collect a library of response samples corresponding to a healthy state [10, 12-13, 22]. This paper presents longitudinal strain data gathered from a 2.3 MW commercial horizontal axis wind turbine tower in order to further facilitate the characterization of a healthy wind turbine tower response to changes in the nacelle's yaw positioning. The turbine was subjected to manually forced yawing of the nacelle during low wind conditions. The data was measured by a Fiber Bragg Grating strain sensor array with the ability to detect both static and dynamic tower response. The strain data is presented as a function of yaw angle and is potentially useful as a healthy baseline as a wind turbine with active yaw control is constantly changing its yaw angle in order to be facing the wind. Future possible applications of the sensor array are subsequently discussed.

II. INSTRUMENTATION

The wind turbine tower studied is 78.54 m tall. It was designed for wind gusts of 59.5 m/s with 18% turbulence. It is comprised of three individual steel sections that are bolted together, the geometry of the sections varies throughout the height of the tower. The bottom section is 15660mm tall with a constant outside diameter of 4200mm and wall thicknesses varies from 41mm to 25mm; the middle section of the tower is 26880mm tall with a constant outside diameter of 4200mm and varying wall thicknesses of 24mm to 14mm; the top section of the tower is 36000mm tall with an outside diameter that varies linearly from 4200mm at the base of the section to 2392mm at the top and wall thicknesses varying from 13mm to 22mm. The tower geometry is such that the area moment of inertia decreases as the height of the tower increases, the moment of inertia of the tower with respect to its height is shown in Figure 2. The large moment of inertia at the base is required to counteract the large bending moment induced at the fixed foundation by the wind design loads [3]. The studied tower was also recently subjected to a comprehensive structural inspection and was determined to be in good condition.

The tower was outfitted with a Fiber Bragg Grating (FBG) sensor array. An FBG array was chosen over a traditional foil gauge set up for a number of reasons

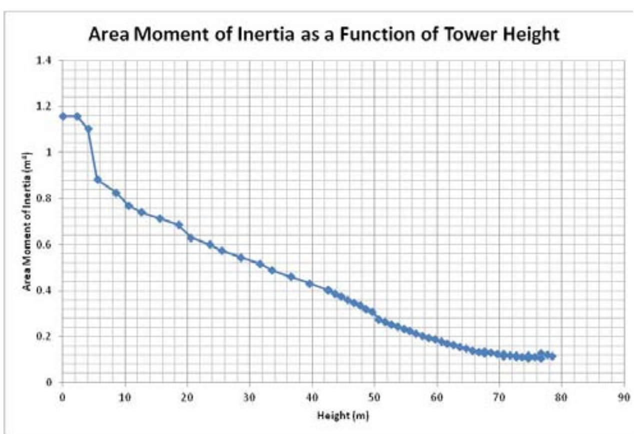

Figure 2:Area moment of inertia of the wind turbine tower as a function of the tower height

including but not limited to; their immunity to electromagnetic interference that may be present during regular operation of the wind turbine [11, 23]. Their corrosion resistance and long service life contributes to their ability to operate for extended periods of time in a variety of harsh conditions such as those experienced by offshore wind turbines in the North Atlantic [6, 11, 23]. Their non conductive nature [23] was of particular importance for this installation given turbine susceptibility to lightning strikes; a 2002 report published by the National Renewable Energy Laboratory found that up to 8% of wind turbines could be expected to experience a lightning strike each year [24]. Strain gauges also have an advantage in measuring static deformations that occur over a long period of time that may otherwise be missed by accelerometers, and are still capable of tracking dynamic responses [6, 9, 11, 23].

The FBG array consisted of two os7100 three dimensional accelerometers, 12 os4100 temperature sensors and 24 longitudinally mounted os3100 strain gauges with a strain sensitivity of 1.4 pm/με, feeding into a sm130 optical sensing interrogator all manufactured by Micron Optics. The strain gauges, and temperature gauges were affixed to the interior of the circular tower by means of an epoxy adhesive at six different heights above the foundation along the tower's vertical axis, shown in Table 1. The vertical location of each of the strain gauge rings were chosen for practical installation with respect to the safety

TABLE I. HEIGHTS ABOVE FOUNDATION

Level	Vertical Height (m)
5	77.34
4	65.02
3	41.84
2	14.46
1	4.46
0	0

landings located throughout the tower. At each level four strain gauges and two temperature gauges were positioned as depicted by Figure 3, with one strain gauge and one temperature sensor at both the 12 o'clock and 6 o'clock position, along with two strain gauges located at the 3 and 9 o'clock positions of the tower respectively. The 12'oclock position corresponds to the true north face of the tower. One accelerometer was placed at level 5 and another was placed at level 3.

As a broadband light source is transmitted through fiber optic cables attached to each strain and temperature gauge, each gauge reflects its own distinct wavelength of light known as the Bragg wavelength λ_B, given by equation 1 below;

$$\lambda_B = 2n\Lambda \qquad (1)$$

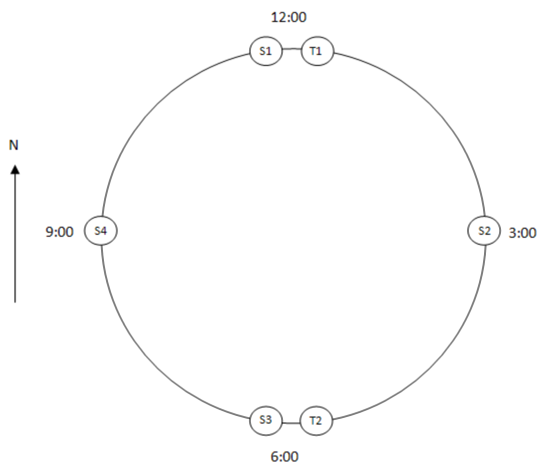

Figure 3: Typical sensor orientation

where n is the effective core index of refraction and Λ the grating period [25]. When a Bragg grating is strained, the grating period shifts, the wavelength strain relationship for a FBG strain gauge is given by Equation 2 below

$$\varepsilon = (10^6)\frac{\Delta\lambda/\lambda_o}{F_G} \quad (2)$$

where ε is the mechanically induced strain, Δλ is the shift in measured wavelength, λ_o is the initial reference wavelength and F_G is a gauge factor which is a property associated with a particular strain gauge that relates the strain measured to the shift in reflected wavelength. It should be noted that the strain gauges are self-referencing. Thus, the strain measured is the change in strain with respect to the original strain reading at the beginning of each experimental recording.

III. EXPERIMENTS

In order to determine a baseline of the relationship between the directional orientations of the nacelle (yaw position) and the strain in the tower at the various strain gauge locations, an experiment was performed on three separate occasions when the wind farm was experiencing periods of low wind, when the wind speeds were lower than the turbines cut-in wind speed of 3 m/s. Low wind periods were chosen for two reasons. First, as the test machine is part of a commercial wind farm, parking a power producing turbine during high yield winds represents financial loss. The second reason was to minimize the proportion of strain response that could be attributed to the wind load. The average wind speeds for each individual experiment are given in Table 2.

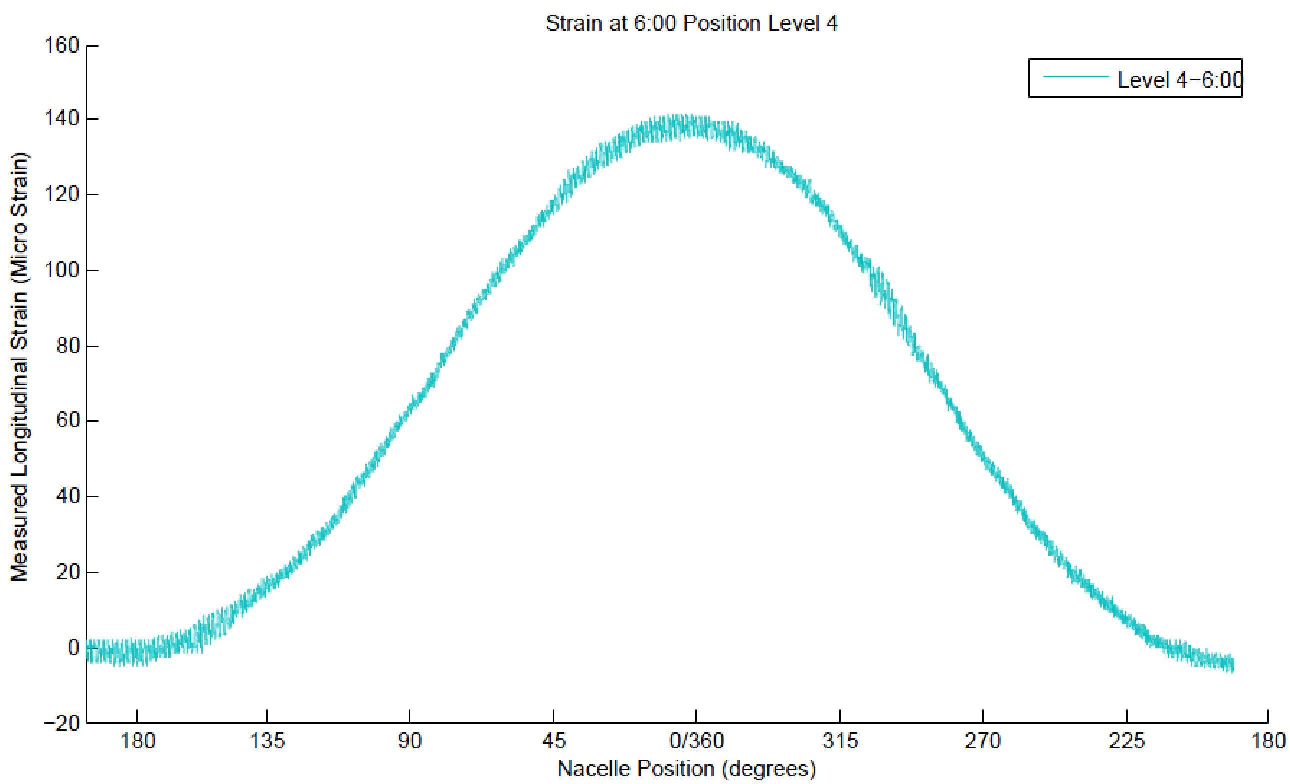

Figure 4: Representative strain-yaw position relationship measured at the strain gauge located on level 4 at the 6:00 position in the tower

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TABLE II. AVERAGE WINDSPEEDS DURING EACH INDIVIDUAL EXPERIMENT

Experiment	Average Wind Speed (m/s)
1	2.1
2	1.5
3	2.5

Each experiment consisted of manually yawing the nacelle, using the tower's handheld control module, for three full 360 degree rotations; each rotation took 800 seconds to complete and was performed in the opposite direction of the previous rotations. The opposing rotation directions were necessary due to the limit of the number of rotations the nacelle can complete in one direction without twisting the cables past their maximum limit. Operational constraints built into the tower's control software also required for the rotor brake to be disengaged while the nacelle was put through the rotations. The blades, however, were pitched into a full aerodynamic brake position to ensure minimal rotor motion during the tests.

Strain information was collected via a PC located at the first safety landing platform inside the tower, running Micron Optics' EN-Light data acquisition software. The sampling rate for the Fiber Braggs Grating array was 100 Hz. The general turbine parameters were recorded on a separate PC located at the wind farm's operations office by means of an SQL script with a data sampling rate of 0.2 Hz. The parameters recorded from the turbine were: nacelle yaw position, wind speed, rotor speed, power production and blade pitch. Before the tests, the two data acquisition systems were set to collect data synchronously with a common timestamp.

IV. RESULTS

The resulting strain-yaw position relationships clearly demonstrate the effect of the eccentric load transferred to the turbines' supporting tower induced by the front-heavy nacelle. This is revealed through inspection of the strain-yaw relationship of any strain gauge in the tower. Figure 4 is representative of a typical nacelle rotation and shows the strain-yaw angle relationship of a strain gauge located at a height of 65.02m above the foundation, situated at the 6:00 position of the tower. As the rotor passes over the gauge (yaw angle of 180 degrees), the tower wall experiences an increase in compressive strain. Similarly, an equivalent tensile strain is experienced when the nacelle is oriented above the opposite side of the tower (yaw angle of 0 degrees), resulting in a predictable sinusoidal pattern in the strain-yaw relationship. Every grouping of strain gauges at each measured tower level between level 0 and level 4 inclusive show a similar sinusoidal response pattern. The difference in strain magnitude from peak to peak for each gauge location shows good agreement with its neighboring gauges as shown in Figure 5. The constancy of the strain response at each level indicates that all strain gauges are functioning properly. The strain peaks for each strain gauge along the rotation of the nacelle occur predictably at a ¼ rotation from the previous peak at 0, 90, 180 and 270 degrees. For the result illustrated here, the nacelle rotated in the counter clockwise direction starting from a yaw position of 194 degrees. The duration of the rotation was 13 minutes and 10 seconds and the mean wind speeds observed at nacelle mounted anemometer was 2.5 m/s.

In order to represent the effect of the tower geometry on the magnitude of strain response induced by the eccentric load at the nacelle, we consider all of the strain gauges positioned on the same face of the tower, e.g., the 6 o'clock position as per Figure 6 below. The tower is constructed such that as the height of the tower increases, the area moment of inertia of the tower decreases. Equation (3) represents the contribution of an eccentric load to the strain induced in a column, where; M is the internal moment induced by the loading eccentricity on the column, y is the distance of the point of interrogation from the neutral axis of the column, E is the elastic modulus of the material, and I the moment of inertia of the column.

$$\varepsilon = \frac{My}{EI} \tag{3}$$

Equation 3 indicates that the strain in the tower is inversely proportional to the area moment of inertia of the tower. This is responsible for the large differences in strain measured along the tower's height as demonstrated in Figure 6. The cross correlation coefficients between every strain gauge along the vertical lines for the bottom 5 interrogated levels of the turbine tower was calculated to range between 0.83 and 0.98, showing good correlation throughout the strain array. This strong and consistent inter-sensor correlation may be applicable to detecting damages within the tower structure by means of a correlation-based damage identification method like that described by Gul [22].

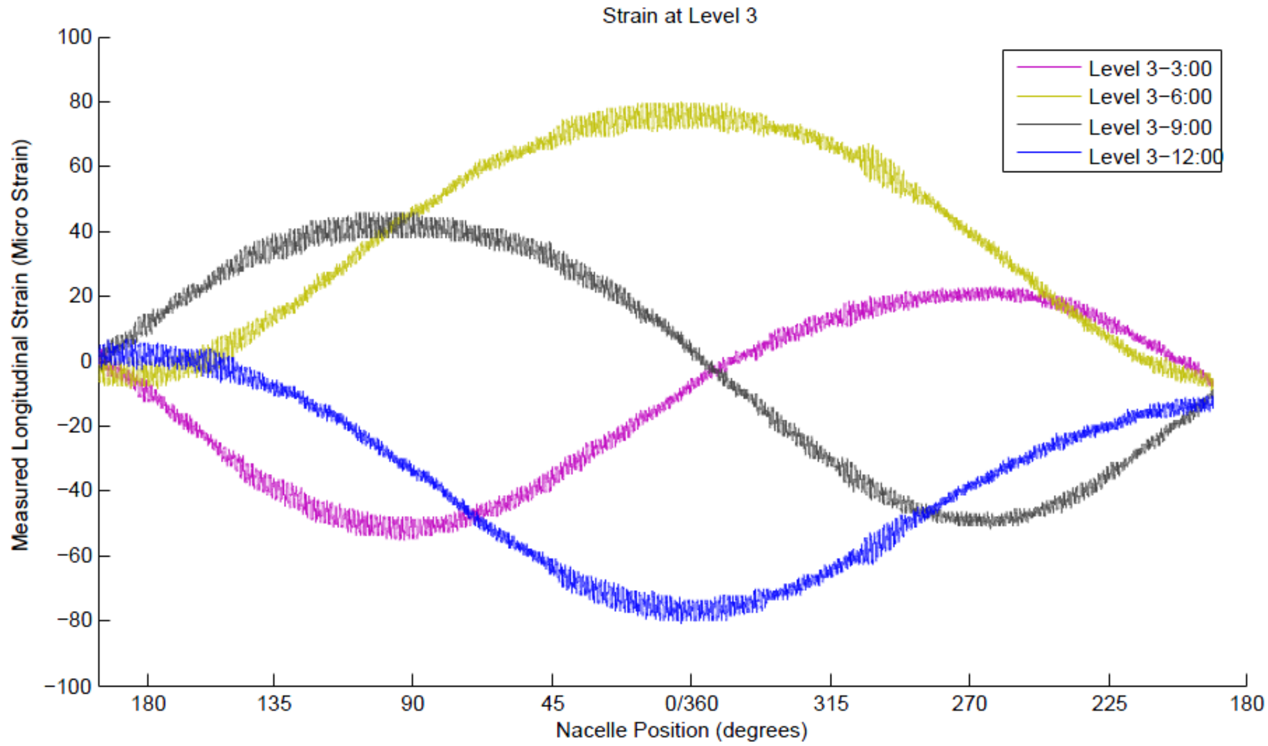

Figure 5: Strain-yaw position relationship measured at Level 3 of the tower.

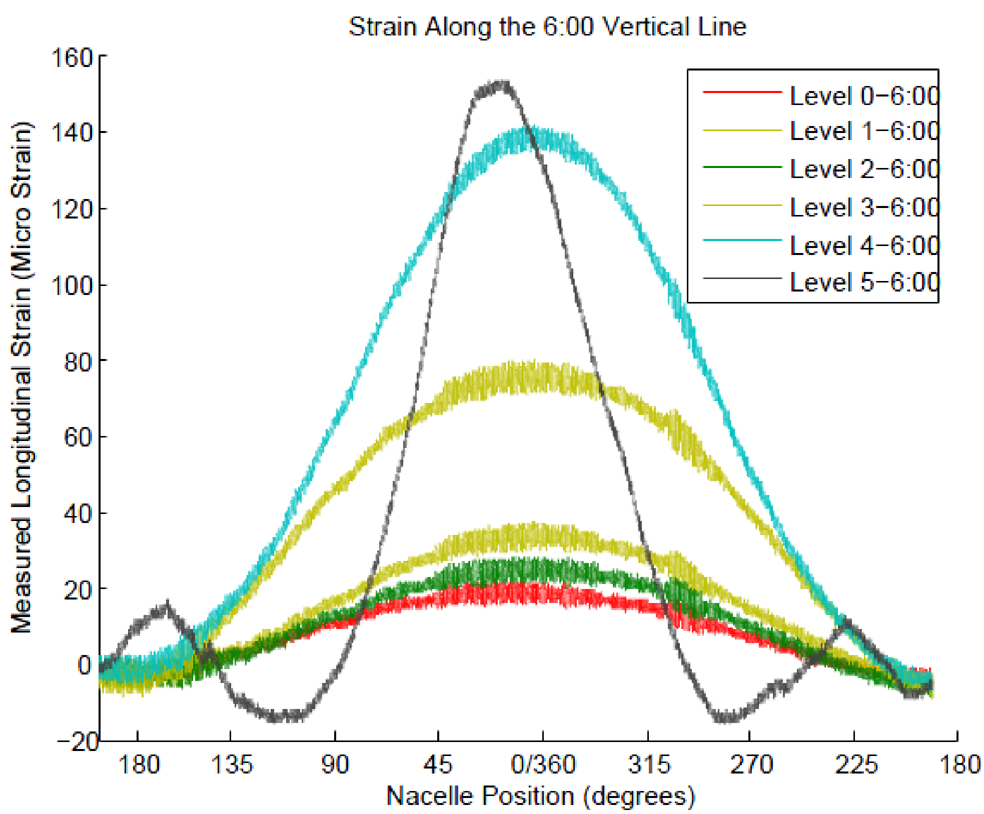

Figure 6: Strain-yaw relationship measured by the strain gauges on the South face of the tower

The difference in strain at 77.34m above the foundation, or the very top ring of strain gauges on level 5, presented in Figure 7, did not behave similarly to all of the other rings below it; rather, each show a large area of peak compression

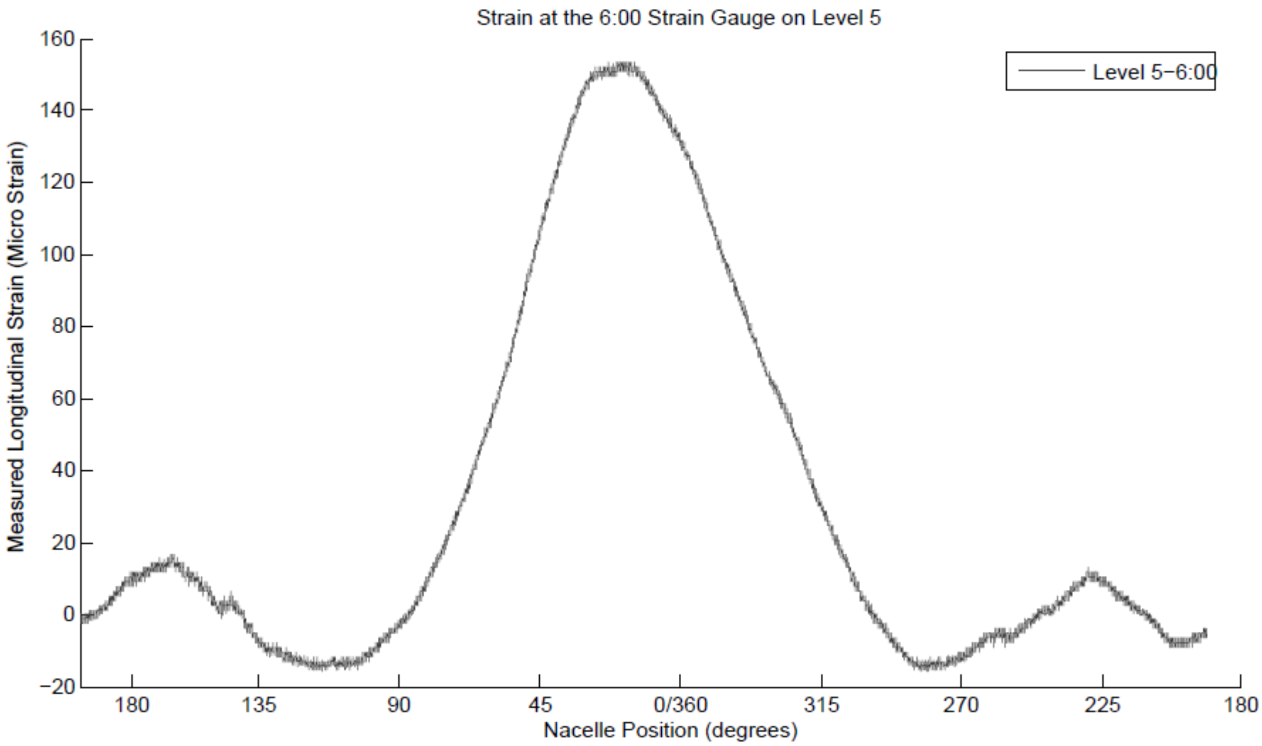

Figure 7: Representative strain-yaw position relationship measured at the strain gauge located on level 5 at the 6:00 position in the tower

within a yaw range of 90 degrees to the left and right of the nacelle current position. It has been theorized that this was a result of the close proximity of the strain gauges to the nacelle load bearing surface, and the possibility of an imperfectly distributed load over the connecting flange transferring a quasi-point load to the left and right of the turbine rotor.

Since yawing events occur constantly throughout turbine operation, the data sets collected and presented can potentially serve as a baseline to which a future SHM program could compare monitored responses. The strong and consistent inter-sensor correlation may be applicable detecting damages within the tower structure by means of correlation based damage identification methods [22]. This set of raw data will be further analyzed in order to identify healthy dynamic response natural frequencies, modal damping, and mode shapes that can be applied to vibration based SHM schemes.

V. Concluding Remarks and Future Work

The structure and instrumentation of a 2.3 MW horizontal axis wind turbine tower using an FBG strain array was described. Three separate experiments held on three different low wind days, investigated the strain response of the supporting tower induced by yawing the nacelle a full 360 degrees. The following can be concluded from the results presented:

- It was identified that the nacelle yaw position-strain relationship demonstrated the presence of an eccentric load transferred to the tower from the nacelle.
- There is the presence of a strong cross correlation between each of the individual responses from the bottom 5 strain gauges oriented along the same vertical line. This correlation could be used as the baseline tower behavior for a correlation-based damage identification method.
- There was a consistent and recurring anomaly in the strain response of the 4 individual strain gauges located at the top level of the tower. It is theorized that the anomaly is a result of stress concentrations at the tower-nacelle interface due to an unequally distributed load.

Moving forward with the results and capabilities of the configured system; the following is being considered: A characterization of the structural response of the tower to different types of rotor braking events. The potential for accelerated fatigue damage promoted through soft, hard, and emergency stops will be studied. Another future work will be focused on the correlation of the tower response due to operational loading measured by means of the SCADA system, a meteorological tower in close proximity to the tower as well as a nacelle mounted LIDAR unit. Finally the system will continually contribute to the development of a database of the healthy structural tower signatures during regular operating conditions.

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Indoor Environment and Energy Efficiency in Higher Schools Buildings

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***Abstract*— The paper presents the main results obtained in a Higher School Building, which are analyzed in view of the actual Indoor Environmental Quality (IEQ) and Energy Efficiency. Measurements were carried out in one building, ventilated by mechanical system. Direct measurements were made with portable monitoring data loggers and in some long-term measurements. The students assessed through questionnaires the IEQ parameters felt in the classrooms a few moments before the end of the class. The IEQ in higher/university schools buildings has been found to be poor because of the high density of students in class rooms. In particular, the Indoor Air Quality is a significant issue for these buildings in order to be healthy and comfortable for learning performance of students.**

Keywords- Indoor Environmental Quality (IEQ), Indoor Air Quality (IAQ), Building Simulation, Thermal Comfort, School Buildings, Thermal Comfort.

I. INTRODUCTION

The sector of buildings is, on a global scale, one of the largest energy consumers (together with transport and industry sectors), becoming essential to ensure a higher energetic and environmental efficiency, thermal comfort and health conditions. Due to high energy prices people are increasingly isolating the buildings and reducing the ventilation rate.

Therefore, it is essential to ensure that they improve their energy and environmental efficiencies, but while ensuring the health conditions. Today we spend 90% of our time inside buildings [1][2][3]. The quality of environment air (outdoor) in cities of developed countries has improved greatly in recent decades. During this same period, IEQ decreased because of energy conservation, reduced ventilation and the introduction of new materials and new sources of indoor pollution. The growing demand for lower energy consumption of buildings resulted in the reduction of heat loss due to transmission by transforming the buildings into closed buildings where the ventilation rates become lower. This fact and the introduction of new building materials can often lead to unacceptable levels of IAQ [4].

There are some investigations that point to lack of knowledge about the effects of poor environmental conditions in classrooms, considering that this type of researches found inadequate school environmental conditions, far worse than in office buildings [5][6][7][8][9].

A. Indoor Environmental Quality (IEQ) and Energy Efficiency

The international standard ISO 7730:2005 [10], developed in parallel with the revised ASHRAE 55 standard [11], considers that a room provides thermal comfort if not more than 10% of its occupants feel discomfort [12]. These studies establish a relationship between the outcome of the energy balance of the body and the trend of dissatisfaction. ISO 7730 standardizes the PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfaction) as the method for evaluation of moderate thermal environments. The standard recommendation for an acceptable environment is -0,5 < PMV < 0,5; PPD < 10 %. Besides the general thermal state of the body, a person may find the thermal environment unacceptable or intolerable if local influences on the body from asymmetric radiation, high air velocities, vertical air temperature differences or contact with hot or cold surfaces are experienced. It was found that persons with lower activity levels (sedentary or standing) are sensitive to draughts, a undesired local cooling of the human body caused by air movement. Occupants who are subjected to draughts in winter tend to elevate the room temperature to counteract the cooling sensation thereby increasing the energy consumption. In extreme cases ventilation systems are shut off or air supply outlets are blocked off with a consequent deterioration of the indoor air quality. Fanger [12] developed a mathematical model to quantify the draught risk in terms of the percentage of dissatisfied people. In this model, the percentage of dissatisfied people due to draughts, DR (%), is calculated from:

$$DR = (34 - T)(v - 0{,}05)^{0{,}62}(3{,}14 + 0{,}37vI) \qquad (1)$$

for v < 0,05 m/s let DR = 0 %
and for DR > 100 % let DR = 100 %.

where T is the local air temperature (ºC), v is the mean velocity (m/s) and I is the turbulence intensity (%), which is defined as the velocity fluctuation over the mean velocity.

The first factor to take into account when carrying out an analysis of air quality is what are the potential contaminants that can be found, their concentrations and the sources of origin [13].

Ventilation is the process of exchanging indoor air (polluted) by outside air (presumably fresh and clean). The main objective is to create better conditions for humans indoors, taking into account the health, comfort and productivity by providing air to breathe (indoor air), which may be through the removal and dilution of pollutants, the removal of pollutants and addition of treated air and heating or cooling.

Several authors have published about the effects of ventilation on health and finds that low ventilation rates can significantly worsen health outcomes, particularly at the Sick Building Syndrome (SBS) [1][2][9][11][15][16][17][18][19][20][21].

Evaluation of IAQ in buildings, according to the Portuguese legal requirements, resulting from the implementation of European directive for building energy efficiency, are defined and specified in Regulation of Energy Systems and Air Conditioning in Buildings (RSECE) [22].

For new buildings, IAQ requirements include minimum values of air exchange (minimum flow of fresh air) per room, depending on the type of activity, and a maximum speed of the indoor air (requirement of thermal comfort) of 0,2 m/s. For existing buildings, IAQ evaluation will verify compliance with same requirements, including maximum concentration of pollutants and maintenance of systems in hygienic conditions to ensure the IAQ (Table 1).

TABLE I. MAXIMUM CONCENTRATIONS REQUIREMENTS OF POLLUTANTS WITHIN EXISTING BUILDINGS (RSECE) [22]

Pollutants	**[mg/m^3]**	**[ppm]**
PM_{10}	0.15	---
Carbon Dioxide	1800	984
Carbon Monoxide	12.5	10.7
Ozone	0.2	0.10
Formaldehydes	0.1	0.08
Volatile Organic Compounds	0.6	0,26 (isobutylene) 0,16 (toluene)
Radon	400 Bq/m^3	
Fungi	500 UFC/ m^3	
Bacteria	500 UFC/ m^3	
Legionella	100 UFC/ L H_2O	

The standard EN 15251:2007 [23] for Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.

II. TECHNICAL WORK PREPARATION

This present work consist essentiality in an evaluation of indoor environmental quality and energy sustainability conditions in a college/higher school building of the Polytechnic Institute of Leiria, located in a temperate climate region of Portugal (Figure 1), ventilated by mechanical systems. The study of higher school buildings has a great importance, not only by the large number of buildings in Portugal, but also due to the high energy consumption, often with low efficiency. Moreover, their occupations are usually a young population, in the process of academic training and are therefore more aware to these issues. It is worth noticing the extreme importance of the study to be undertaken in this research area, because significant numbers of evaluations in such buildings are not known, in Portugal. The School of Technology and Management of Polytechnic Institute of Leiria (ESTG) has currently about 6000 students and consists of modern buildings (Building A, B, C, D, E, and Library).

Figure 1. IPLeiria Plan View of Campus II - *Building D.*

Building D (Pedagogic building) - The building is 8851 m^2, is a recent building (2004) and has a L-shaped implantation and have plenty of areas provided with glass. The building has a maximum valence for this type of use, which consists of many classrooms, laboratories, computer rooms, reprography rooms, auditoriums, rooms for storage, toilets, coffee-shop/bar area, offices for teachers, meeting rooms and passage areas. Its ventilation system is mechanical (heating, ventilation and air conditioning-HVAC) and has a capacity of 985 occupants.

Direct measurements with portable monitoring data loggers were carried out in the *Building D* of the Campus II of IPL, belonging to ESTG. The measurements were carried out in the winter and summer season. Measurements were made by long-term continuous and by point sampling, with portable monitor equipment always following best practice recommendations for audits of IEQ and Energy Efficiency as much Portuguese as ISO 7726 [17].

The study of indoor environmental quality and energy efficiency of buildings higher education becomes increasingly important, not only because of its complexity due to various factors, which emphasizes the large number of variables that influence performance, as due to its subjective nature and the fact that the buildings were made of areas with different purposes often enough and the high number of users. Due to the complexity of this research, analysis was done into two points of analysis:

1. Energy analysis
2. Analysis of indoor environment quality

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III. RESULTS

These results reflect the reality found in *Building D* through direct measurements and questionnaires made during one year.

A. *Energy analysis*

The electric energy consumption on *Building D* was compared to one measurement in the power station. Figure 2 represents the diagram of charges in the building.

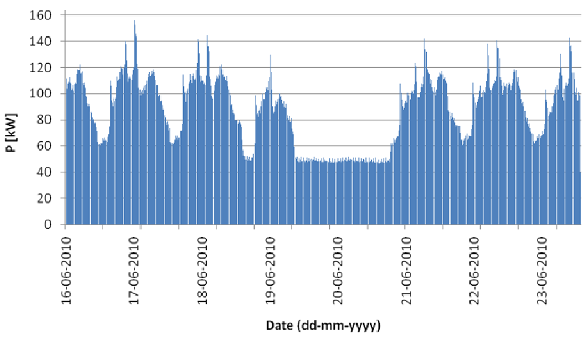

Figure 2. Diagram of charges in the Building D

The measurement of energy consumption on a daily basis is a reasonable range of recording, it can be used to distinguish between weekdays and weekends and disaggregating energy end uses is essential to validate the model.

The electric energy consumption verified on *Building D* was dissociated between the computer center, the HVAC, cooling and the rest of the building, as presented in Figure 3.

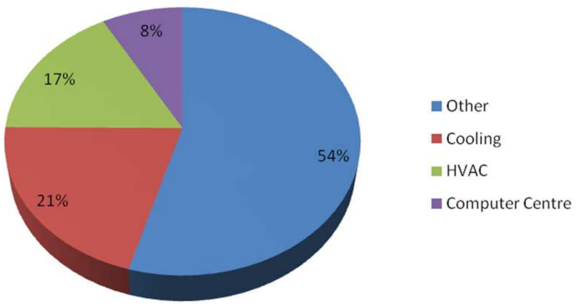

Figure 3. Dissociation of *Building D* consumption

The computer model of *Building D* (Figure 4) is properly calibrated and validated with the field measurements as a way to improve Indoor Environment Quality (IEQ) and the energy efficiency of the Building.

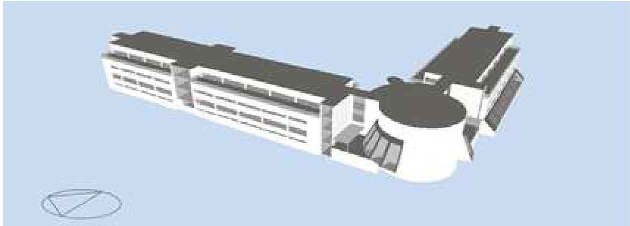

Figure 4. View of Building D (DesignBuilder)

The dynamic simulation has four distinct cases:

Case 1. The closest possible to the actual case study (real consumption of *Building D* – Calibration Model);

Case 2. The reference values and schedules of the Portuguese legislation for Higher Education Buildings (Spain does not provide recommended values for these cases);

Case 3. Conditions optimization (schedules, temperature set points, computers, office equipment and lighting improvements, lighting and shadow control).

Case 4. Same conditions as Case 3 but with the reference schedules of the Portuguese legislation for Higher Education Buildings.

The different case simulations are performed on *DesignBuilder / EnergyPlus*. The Table II presents some of the simulation results.

TABLE II. SIMULATION RESULTS

Simulation results	Case 1	Case 2	Case 3	Case 4
CO_2 (kg)x10^3	715,71	722,82	437,93	314,16
Relative Humidity (%)	46	45,94	47,38	48,38
Fanger (PMV)	0,5	0,45	0,41	0,34
Mech Vent + Nat Vent + Infiltration (ac/h)	0,63	0,61	0,63	0,63

The simulation results (Figure 5) show that appropriate operational mode could greatly improve the energy consumption.

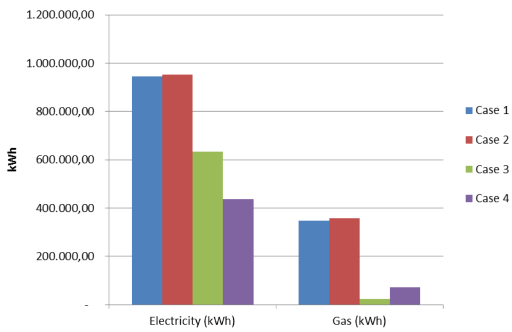

Figure 5. The consumption for the different cases

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B. Indoor Environmental Quality

The values obtained by direct measurements were validated by the thermal votes of the students and teachers to the same environment predicted by questionnaires, obtaining subjective results. Figures 6 and 7 present air temperature results in the winter and summer season, according to EN 15251[23].

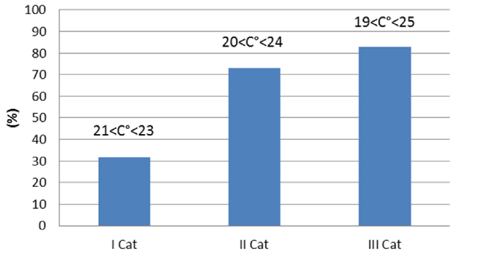

Figure 6. Temperature values recorded for winter season

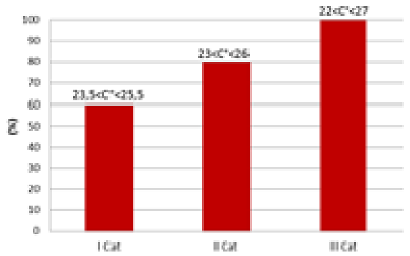

Figure 7. Temperature values recorded for summer season

Concerning the thermal comfort conditions, it enables the analytical determination and interpretation using calculation of PMV and PPD index and local thermal comfort criteria.

The values of PMV and PPD were calculated with 1.2 met and 1.0 clo (winter season) or 0.5 clo (summer season), and according to the EN 15251 [23] (Figures 8 and 9).

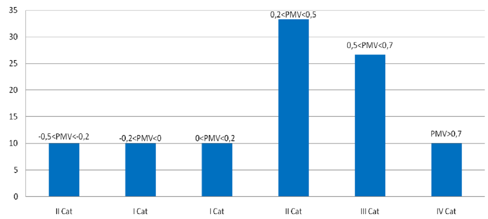

Figure 8. PMV values recorded for winter season

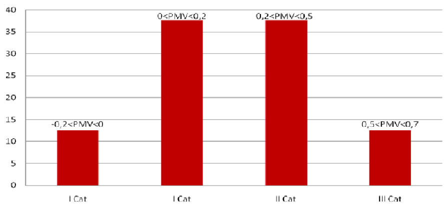

Figure 9. PMV values recorded for summer season

Figures 10 and 11 present according to EN 15251 [23], the subjective results called Expressed Mean Vote (EMV).

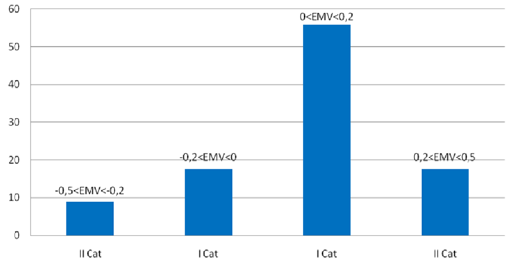

Figure 10. EMV values recorded for winter season

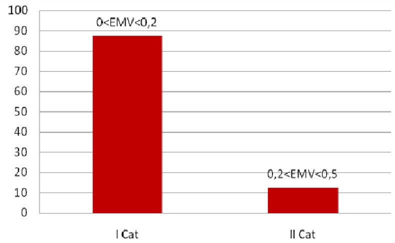

Figure 11. EMV values recorded for summer season

Field experiments of local thermal comfort criteria, based in the local air velocity, temperature and the turbulence intensity, were used to calculate the draught risk in terms of the percentage of dissatisfied people (DR). Figure 12 and 13 presents an example of air velocity and DR obtained in a classroom with different systems of ventilation.

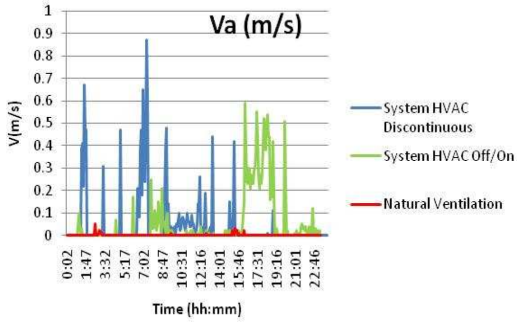

Figure 12. Typical air velocity

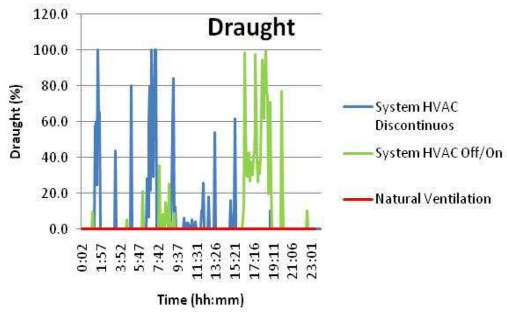

Figure 13. Percentage of dissatisfied due to draught risk

Concerning the indoor air quality evaluations, a representative typical example of experimental CO_2 values obtained in some classrooms is presented in Figure 14 for a classroom in a building with natural ventilation, for discontinuous HVAC conditions (because the system turn on and off all day), and for a HVAC Off/On conditions (which mean that the system has off until the middle of the day and after it has turn on).

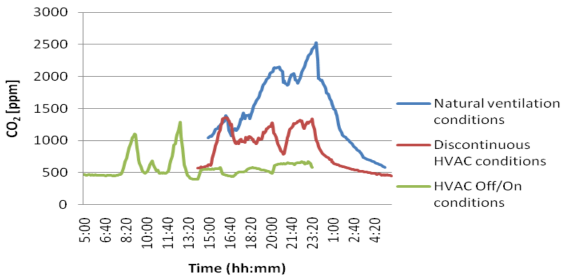

Figure 14. Experimental CO_2 values

As expected, the concentration of CO_2 and the relative humidity changes according to the occupancy conditions (number of peoples and length of time).

Furthermore, the EN 15251 [23] suggest several levels of CO_2 above outdoor, corresponding to different quality categories. For winter season the average of the measurements CO_2 outdoor was equal to 458 ppm and for summer season the average measurements of CO_2 outdoor was 401 ppm (Figures 15 and 16).

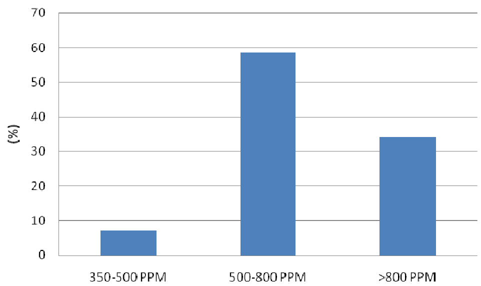

Figure 15. CO_2 values recorded for winter season

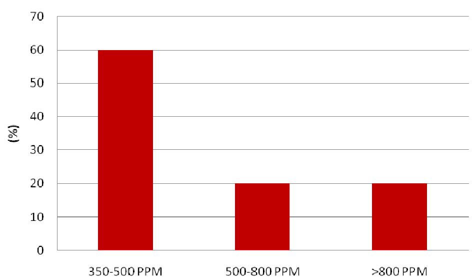

Figure 16. CO_2 values recorded for summer season

In the indoor environment of classrooms in winter, there are high concentrations of CO_2.

IV. DISCUSSION AND CONCLUSION

The measurements made during this study allow us to reach the following conclusions:

There are some building intrinsic properties, which affect the internal conditions but another key aspect is the behaviour of the occupants and their actions that affect the internal conditions.

The dissatisfaction due to draught is caused, in many cases, by air velocity and turbulence intensity.

Results show and demonstrate that ventilation is a very important issue. Different operating modes can deliver to different results which might lead to take decisions, often unsatisfactory. The recommended solution is the hybrid ventilation systems. The key problem is to provide the total control system, sufficient but not excessive ventilation, avoid drafts, etc.

Comparing the ventilation rates achieved, represented by air changes per hour, with the ones recommended by standards, and due to relative errors, it was concluded that the temperature of air, carbon dioxide levels, formaldehyde, bacteria, fungi and air change rates are many times at unacceptable levels. The measurements made indicate that is convenient to maintain the temperature and relative humidity of the buildings on lower levels of thermal comfort.

The objective and subjective results obtained in our study, allow us to state that the building has acceptable levels for different environmental factors.

Is also clear that modelling is a very important activity for sustainable construction engineering. However, there still a set of important problems. The full integration of energy and indoor environmental quality modelling and design projects, requires the integration of additional processes and especially, more research regarding how to make decisions, and in the manner of how the results of modelling can help to make choices in this type of buildings.

The Building Management System (BMS) should be able to respond to these dynamics (the indoor air temperature, CO_2 level, the automatic control of naturally ventilated building, occupancy, humidity, rain detection, outside air temperature, wind speed and wind direction sensors) and be capable of a resolution to operate both in the cases of high occupancy (high density), as in the cases of low occupancy (low density).

More efficient temperature set points can reduce the energy consumption of Higher Education Buildings. Therefore, efforts should be made to reach new reference standard values. The simulations show that small changes have quick paybacks. We can reach over the 50% of improvement (Case 4).

New energy efficient technologies are needed to achieve the new directives; the development may require an understanding of the mechanisms by which the indoor environmental quality affects humans.

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