A Holistic Framework for Environmental Impacts of Consumables in Production Tools to Enable Optimisation

By

Katharina Posten, B.Eng.

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Supervisors: Dr. Paul Young, Dr. Brian Corcoran

School of Mechanical and Manufacturing Engineering
Dublin City University

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For Taliha, Melisa, Bríon, Linus and all their future cousins

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Abstract

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Energy and resource efficiency are key for establishing a sustainable manufacturing sector. For this, a holistic environmental impact assessment methodology is required which combines environmental regulations and energy efficiency methods to give standardised environmental impacts that can be easily compared across different products. Focussing this method on production tools maximises the savings enabled through this standardised approach, as they directly affect all other factory systems. The methodology has to include not only the volume of consumption of substances used but also their embedded footprints of energy, greenhouse gasses and other environmental aspects such as toxicity or eutrophication. Including these allows the methodology to balance substances against each other whilst keeping in mind tool consumption rates and tool operation. For complex manufacturing tools, the selection of which substances to monitor is another important consideration, to allow widespread adaptation of the methodology.

This research developed a holistic environmental optimisation methodology for resources used in dynamic processing tools, without the need for experimentation. It is based on transparency and key environmental performance indicators and allows dynamic modelling of tool behaviour to find holistically optimised consumption rates. Usage data obtained from a production tool is used to show the application and validity of the methodology.

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Nomenclature

CSR	Corporate Social Responsibility
DAQ	Data Acquisition
ECFs	Energy Conversion Factors
EHS	Environmental Health and Safety
ELCI	European LCI Database
EPI	Environmental Performance Indicators
Fab	Semiconductor Fabrication Facility
FFU	Flexible Fan Units
GHG	Greenhouse Gas
GHGP	Greenhouse Gas Protocol
GWP	Global Warming Potential
ISMI	International SEMATECH Manufacturing Initiative
ITRS	International Technology Roadmap for Semiconductors
KPI	Key Performance Indicators
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LEED	Leadership in Energy and Environmental Design
PCW	Process Cooling Water
POST	Posttool Impact
PREF	Prefactory Impact
PRET	Pretool Impact
SEAJ	Semiconductor Equipment Association of Japan
SEMATECH	Semiconductor Manufacturing Technology
SEMI	Semiconductor Equipment and Materials International
SETAC	Society of Environmental Toxicology and Chemistry
TEE	Total Equivalent Energy Tool

Publications

Conference Papers / Presentations

Posten, K., Young P., *"Holistic Optimisation of Environmental Resources in Complex Production Tools"*, International Manufacturing Conference 2011 (IMC 28), 30 August – 1 September 2011, Dublin City University, Ireland

Posten, K., Young P., *"Measure, Compare, Optimise … Standardise? Holistic Environmental Footprint Quantification"*. Presentation at the Intel European Research and Innovation Conference 2010, October 2010, Leixlip, Ireland

Posten, K., Young, P. *"Aspects of Energy Consumption Reduction in Complex Manufacturing"*, International Manufacturing Conference 2009 (IMC 26), 2-4 September 2009, Trinity College Dublin, Ireland

Fitzsimons, L., Posten K., Corcoran, B., Young P., *"Energy Reduction in Semiconductor Manufacturing"*, Presentation at the Intel European Research and Innovation Conference 2008, 10-12 September 2008, Leixlip, Ireland

Abstracts/Posters

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Posten K., Young P., *"Production Tool Environmental Efficiency"*, Abstract and poster for the IRCSET Symposium 2009, 25th September 2009, Dublin, Ireland

Posten K., Young P., *"Production Tool Environmental Impact – An Analysis Methodology"*, Extended abstract and poster for the Intel European Research and Innovation Conference 2009,8-10 September 2009, Leixlip, Ireland

Posten K., Young P., Corcoran B., *"Production Tool Energy Usage, Measurement and Optimisation"*, Extended abstract and poster for the Intel European Research and Innovation Conference 2008, 10-12 September 2008, Leixlip, Ireland

Chapter 1 Introduction

1.1 Motivation

It is well known that there is an increasing scarcity and insecurity in resource supply. With increasing manufacturing of resource intensive products, it is clear that there has to be a change in the global community's approach to manufacturing. There are two main ways to enabling sustainable resource consumption. One is by supplying more efficient products to the consumers, whilst the other is to optimise the production processes. Up to now, the main focus has been on energy efficiency, in terms of its production and its consumption in products and factories. Much of this effort focussed on the end consumer and their usage of products, which manifested itself in more energy efficient cars, lighting, heating and housing. This emphasis on products can be seen in rating systems such as the Energy Star Rating [1].

However, what is often neglected is the part that the manufacturing of the goods takes in this. The environmental impact created by the production tools in a production facility, whilst creating these perceived efficient products, is often overlooked or disregarded. However, this resource consumption of manufacturing is hugely important when considering the limited supply of each resource. Whilst the fragility of energy supplies is well documented and present in the media, resources scarcity for water or other consumables such as precious metals, e.g. Lithium, is given very little representation. Similarly, the impact created on the environment by sourcing and producing the consumables used in manufacturing is often overlooked if products and factory systems are optimised or addressed for their energy footprint alone. Using a one sided approach will lead to a shift of environmental impacts from visible consumables, such as energy, to hidden ones such as chemicals used, which are less regulated and not seen by the public eye. Even with regulation, such as CO_2 trading caps or chemical release regulations, there will be a shift to different, less regulated chemicals in order to circumvent these.

However, to achieve a truly sustainable global community, every aspect of product manufacturing needs to be scrutinised, including the hidden environmental impacts of all consumables used and the impact created in the factory itself. Therefore, a shift needs to occur from focussing on the products efficiency to the environmental efficiency of the production process, without losing the efficiency gains made in the product, but rather as an inclusive view of both. This also means a shift of focus away from the consumer towards industry and its environmental resource efficiency. This means production tools and the consumables used in them should be the focus.

One problem is how to illustrate the footprint behind products, if there is no correlation between the mass of resources used and the mass of the final product, such as a microchip. This is especially true for complex products like those found in semiconductor or biotechnology industries. In such complex manufacturing settings, the production tools determine the overall resource consumption, not only through the actual production process but also by demanding tightly controlled production environments, which themselves are resource intensive.

Although methods for industrial resources efficiency exist, especially in terms of energy and restriction of release of harmful substances to the environment, few of them focus on all consumables and especially on the interaction of consumables with each other. For this, a more holistic methodology must be developed, that focuses on all consumables as well as on their interaction in the tool and their support systems. Existing methodologies, such as Life Cycle Analysis (LCA) or the ISO 14000 [2] environmental management standard, often focus on the static characteristics of the production site, such as annual averages, and onto the product environmental impact. However, including the dynamic behaviour of production processes is a primary pre-requisite for optimising the inherently dynamic factory and processing tool characteristics. Additionally, most existing methodologies are very complex in their demands, but supply little guidance to their execution. This leads to differing results, which can be tailored to suit the best result for the company rather than accurately describe the environmental impact.

When focussing on production tools, it is important to develop methods to capture the optimisation potential of legacy tools. Whilst new tools are constantly improved in terms of consumption, legacy tools are generally not optimised once installed, especially in complex manufacturing. However, legacy tools offer great potential for optimisation, in terms of numbers of existing units as well as low hanging fruit, for example during their idling phases.

1.2 Research Objective

This research will develop a framework for assessing legacy tools in terms of their environmental impacts and their dynamic consumption behaviour. This framework will have to be transparent so that hidden environmental impacts are captured and no shifting of impacts upstream or downstream can occur.

The key to this is to enable communication between factory owners, technicians and experts. This will be done by visualisation of the environmental impacts created in the factory as well as upstream and downstream of it, therefore including the embedded footprint of consumables used as well as the effect onto the environment of the emissions from the production. The visualisation uses Key Performance Indicators (KPIs) to show summarised environmental groupings, which gives meaning to the otherwise vast amount of impact data without helpful interpretation of it.

Additionally, a transparent decision making standard has to be introduced that allows selection of consumables to monitor, in order to reduce overall measurement effort, which is lacking in existing methods. This framework of transparent environmental footprints and selective measurement then enables optimisation methodologies for overall environmental optimisation.

This method will make a contribution in the organisation of industry after the second industrial revolution, where resources are scarce but people power is abundant. This will hopefully lead to a more sustainable manufacturing practice with a focus on overall efficient products, in their original production as well as their own usage by the consumer.

1.3 Structure of Document

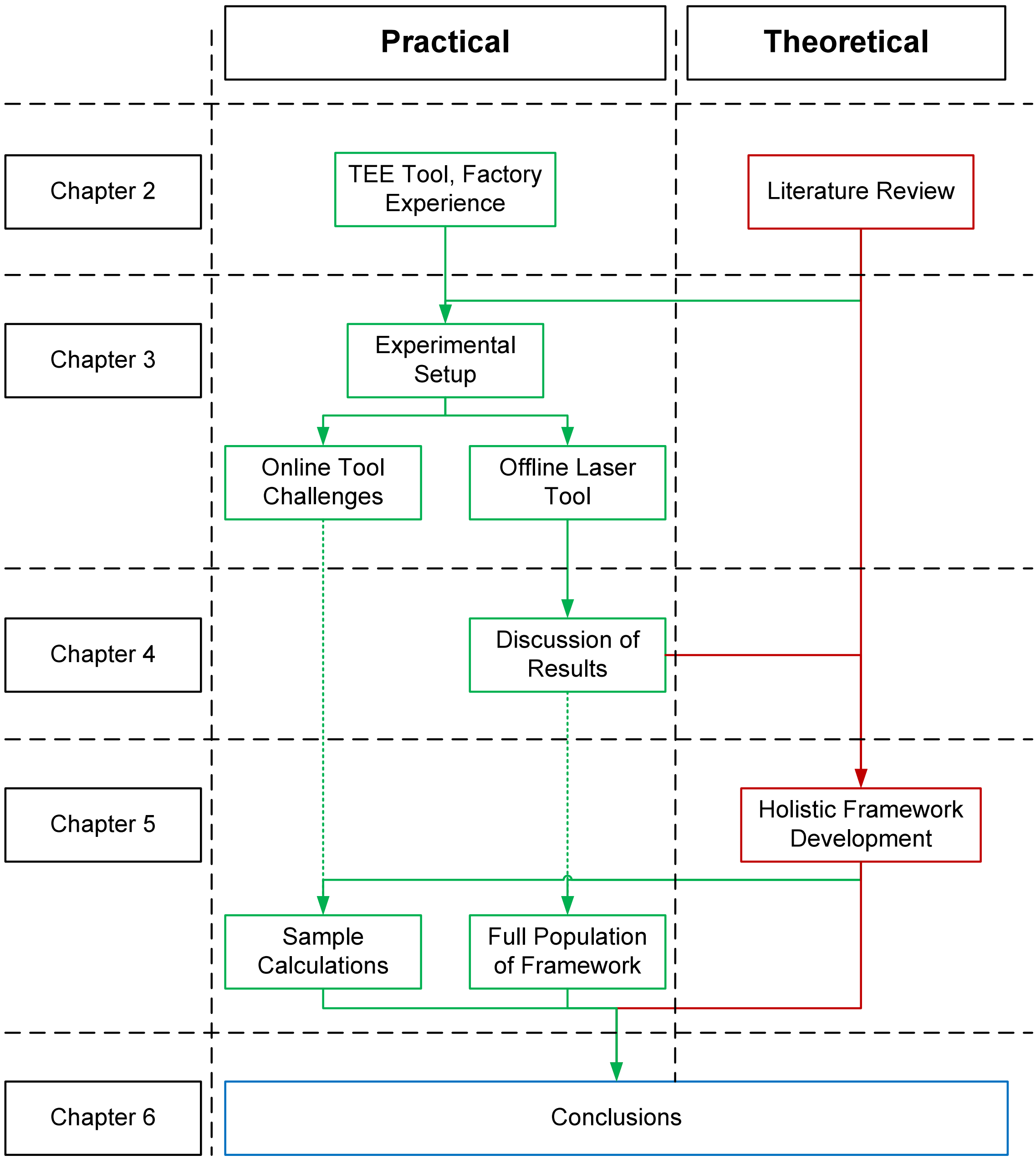

Figure 1-1: Structure of the Thesis Research

Figure 1-1 shows the structure of the thesis, which is comprised of a theoretical component covering the Literature review and the development of the holistic framework, as well as a practical component which shows the factory experience, the instrumentation of a laser cutting tool and the application of the theoretical method to the results.

This thesis investigates the currently prevalent environmental assessment methods and the challenges for industrial application of these. It then analyses two production tools in terms of their consumption volumes and finds consumption patterns. With these patterns a new environmental assessment methodology is developed which is practical and focussed on the production tools in a factory.

Chapter 2 reviews the literature found in terms of industrial energy consumption, efficiency and assessment methodologies. It also shows the challenges associated with them, such as transparency, standardisation and reproducibility. It investigates the semiconductor manufacturing industry's management of energy efficiency and the problems associated with currently used measurement units and methods.

Chapter 3 investigates two production tools in terms of consumables used and challenges of data acquisition from them. One is a semiconductor manufacturing tool which shows the internal complexity of production tools and the challenges of instrumenting them. The second is a simpler laser cutting tool which is subsequently fully instrumented to allow analysis of dynamic consumption patterns.

Chapter 4 describes the consumption volumes and patterns of the different consumables in the CO_2 laser cutting tool. The consumables vary considerably in their behaviour in different production phases, and show relationships between the different consumables and measurements at different production stages.

Chapter 5 introduces a new practical approach for assessing the environmental impact of production tools. This is based on key production tool measurements and the embedded environmental impacts of the consumables it uses. Additionally the environmental impacts are defined by KPIs that allow a consistent, reproducible and standardised total holistic impact of each consumable to be determined. Using the holistic impact and the production tool measurements, areas for optimisation can be identified which optimise the overall environmental impact, whilst taking into account the entire supply chain of the consumable. This method is then applied to the results from Chapter 4, of the laser-cutting tool, to show where wastage occurs and where optimisation is suggested. Additionally, sample impacts are calculated for a more complex semiconductor manufacturing tool.

Chapter 6 draws the conclusions from the research presented in terms of novelty, development and future work.

Further information and programs written are found in appendixes A-F.

Chapter 2 Literature Review

2.1 Introduction

To create a sustainable global economy, two key factors need to be addressed. On the one hand, the supply of resources such as energy and water has to be secure and sustainable. This is currently investigated and implemented, for example in terms of renewable energy supply. On the other hand, the demand for resources has to be curtailed and inefficiencies in supply chains removed and direct consumption reduced. One main factor in this is the reduction of cheap, fossil fuel based energy supply. Although energy costs for residential and industrial customers have risen in the past decade, as shown in Figure 2-1 and Figure 2-2, they are still not in-line with the prices expected for sustainably produced energy.

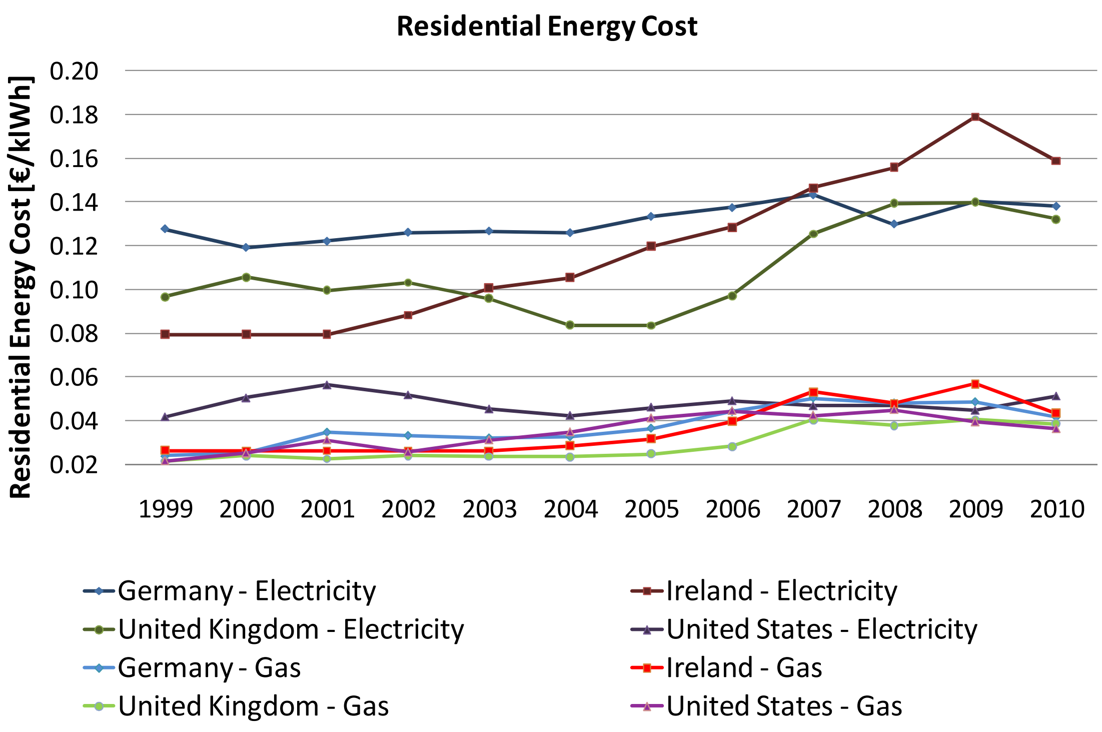

Figure 2-1: Residential energy prices for electricity and natural gas for Germany, USA, UK and Ireland, from [3-5]

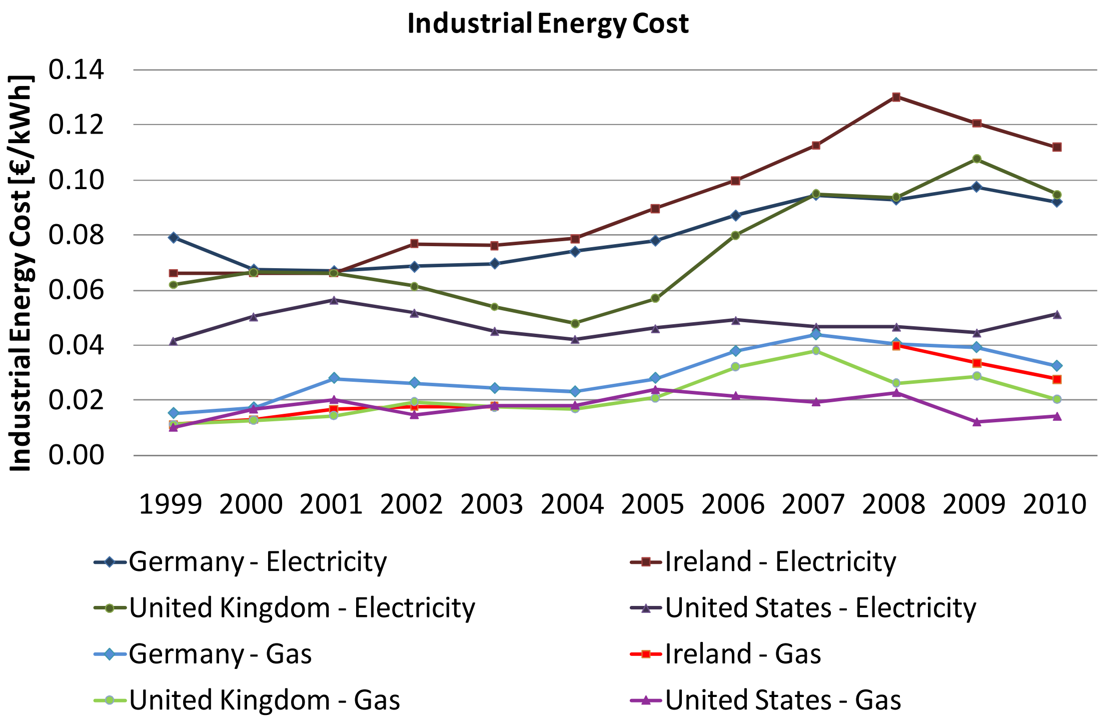

Figure 2-2: Industrial energy prices for electricity and natural gas for Germany, USA, UK and Ireland, from [3, 6, 7]

For example, residential electricity cost in Ireland has doubled between 1998 and 2008, from 0.08€/kWh to 0.16€/kWh, and similar trends can be observed in most countries for gas and electricity prices, as well as industrial prices, as shown in Figure 2-2. This highlights the benefit of demand side reduction for immediate reduction of resource supply, whilst more sustainable methods of supply are developed and implemented.

An analysis of the nationwide energy consumption for the United States, Germany and Ireland - in four consumer sectors of residential, industrial, commercial and transportation – highlights additional targets for demand reduction, as shown in Figure 2-3.

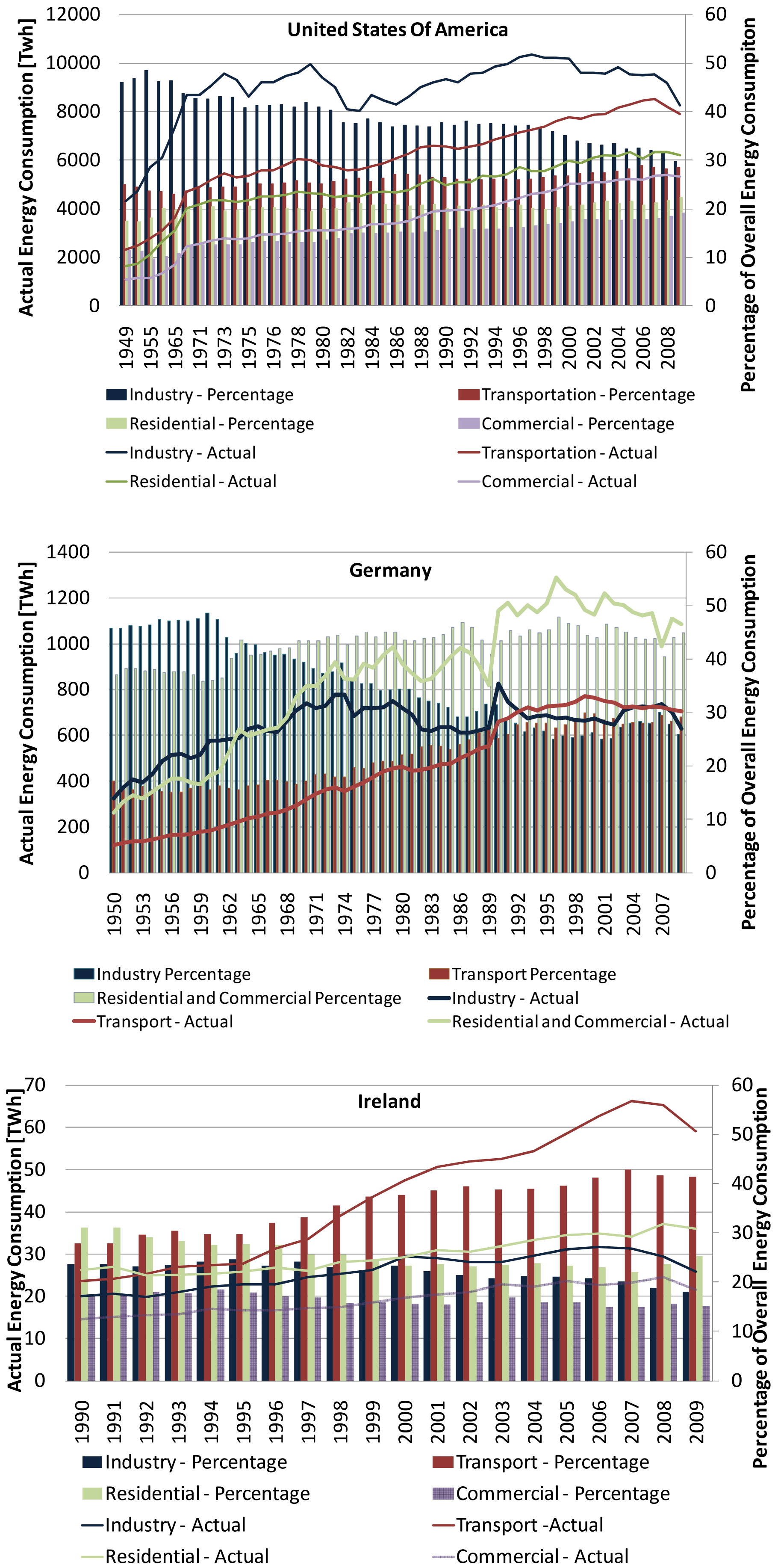

Figure 2-3: Energy consumption rates of different sectors for USA, Germany and Ireland [8-10]

It can be seen that the actual values for all four sectors have increased steadily over the past five decades in Germany and the USA, and that the residential, commercial and especially the transportation sector have increased at a much faster rate than the industrial consumption. This means that the percentage of the still dominating industrial sector has actually decreased from 45% to 30% in the USA and from 45% to 25% in Germany.

One noticeable point is that of all three sectors, the transportation sector is the fastest growing one, tripling in Ireland over the space of a decade and quadrupling in the USA over 60 years. Overall though, it can be seen that industry is generally dominant, except in Ireland where much less heavy industry[1] is located compared to Germany and the USA. However, when the total energy consumption is related to the number of units per sector, industry's dominance is highlighted again.

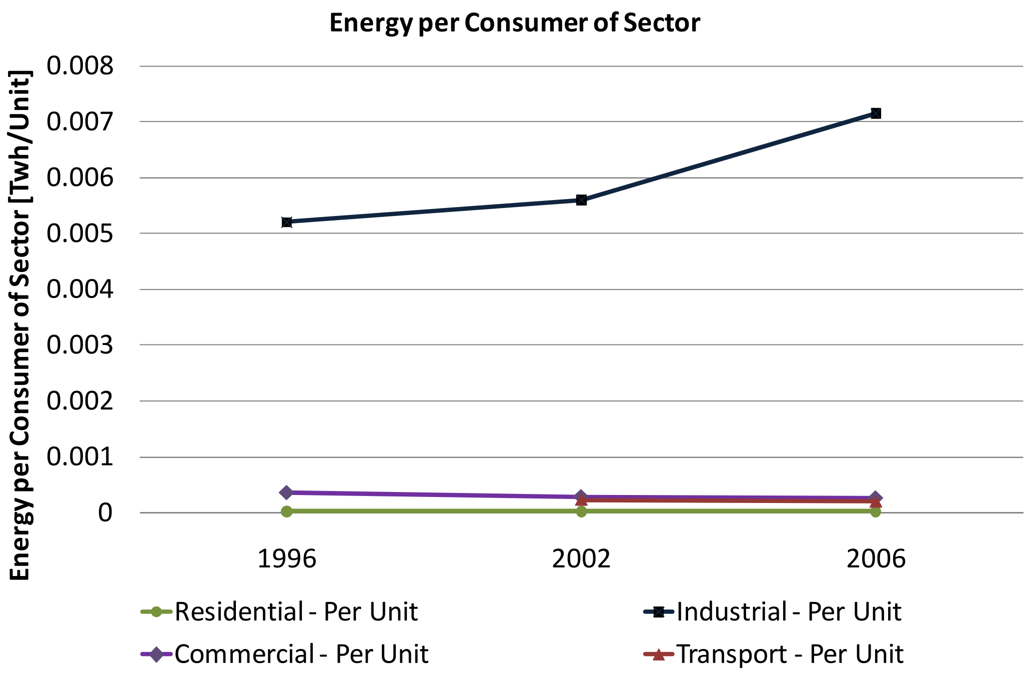

Figure 2-4: Energy per consumer for Ireland [11-13]

[1] Heavy industry here is defined as industries, which consume large quantities of resources and contributes large amounts of emissions, for example steel production, but also complex, high volume industries such as semiconductor manufacturing qualify. Compared to light industry, which has few emissions and very little raw material inputs.

Currently, there are 5,000 industrial units in Ireland, compared with 1,000,000 residential units and 300,000 transportation units [11-13]. Combining this with the total energy consumption per sector, as shown in Figure 2-4, it becomes clear that the focus of energy reduction should be on the industrial consumption. It is currently seven times more energy intensive than the other three sectors, which are all under 0.0005 TWh/unit.

Additionally, due to industry's role as manufacturers of consumer goods, and consequently facilitating the usage of more energy and resources through their products, it is important that industry takes a lead role in the global drive for resource consumption optimisation and in creating a sustainable global economy.

2.2 Management and Measurement of Industrial Resource Consumption

In industry, energy cost was generally associated with a fixed annual cost. However, with the recent increases, energy cost has changed from being a small percentage of the overall budget and product cost (around 1-2% [14]) to being a major contributor of the overall product cost, and has become a focus for cost efficiency measures and environmental efficiency measures.

To effectively measure, monitor and manage the energy consumption of a company, a standardised strategy is required. Over the past five decades, different approaches and methodologies have been developed for energy monitoring, and these methods increasingly include environmental monitoring, to optimise all resources and emissions caused by a particular company. For this environmental monitoring, all aspects of the impact of a consumer product onto the environment have to be included – from the environmentally responsible sourcing of raw materials over resource production to manufacturing, product packaging, transport, product usage and disposal/recycling.

Two main approaches exist that try to enclose the full environmental impact created by production: Life Cycle Analysis (LCA) and the Greenhouse – Gas Protocol (GHGP).

LCA is generally defined as a

"compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" [15].

It has been established over the past 20 years as the leading way to determine the environmental impact of products and services. Standards like the ISO14000 series[1] [2] supports its implementation and through focus groups like the Society of Environmental Toxicology and Chemistry (SETAC) a workable standard for LCA for products has been achieved. A good introduction and guideline is given in Guinee's book [15]. LCA mainly focuses on high level observation and data is often at the factory level rather than lower level factory systems such as production areas or production tools. As environmental impacts are global, due to different production sites and sourcing of materials etc [15, 16], local factory impacts cannot be identified, nor can any lower level impacts be attributed. Additionally, LCA focuses on the steady state phase of the product life cycle [15]. However, to optimise manufacturing processes, dynamic factory changes have to be considered as well, and are often decisive in determining the actions

[1] The ISO14000 series is an environmental management standard similar to the quality management series ISO 9000. The basic part of this standard is structured similar to ISO 9000 and hence is easily implemented with quantifiable benefits when focussing on factory level consumption and management. The further one goes into the ISO 14000 standard, the more detailed measurements are required and the time and personnel effort increases. LCA, as a tool for total environmental tracking, is introduced and regulated in ISO 14040.

to be taken. Similar standards such as the British PAS 2050 Standard [17, 18] for Carbon-footprinting of goods and services or the Irish IS393 Standard [19, 20] for Environmental Management again only focus on the product and on the static characteristics of the factory.

The World Resources Institute developed the GHGP [21], which focuses mainly on the greenhouse gas (GHG) consumed by a company, and can be broken down into three distinct areas: Scope 1 is concerned with direct emissions from the factory, i.e. measuring the emissions outlined in the Kyoto Protocol. Scope 2 estimates the GHG released from electricity generated off-site but used on-site. Scope 3 leaves room for reporting any other important emissions, as well as conducting an LCA or calculation for losses in the system previously overlooked. Currently companies participating in the scheme are only required to report two out of the three scopes, with most companies choosing Scope 1 and 2 emission reporting. However, similar to LCA, there is no relationship established between inputs and outputs of the system and there is no recognition of dependencies between different inputs and outputs.

Both of these approaches feed into the idea of Corporate Social Responsibility (CSR) reporting, which highlights, measures and shows achievements within a company towards social and environmental issues. When CSR was first introduced, project claims and the data they were based on were largely unregulated and non-reproducible. With regulation of LCA through the introduction of the ISO 14000 series and the GHGP, the quality and accountability of the reports and the data generated have greatly improved. The downside of the drive to environmental reporting is that green-washing can occur in these reports. This means that whilst certain, positive environmental issues are reported, negative impacts are neglected and not focussed on in the environmental optimisation drive of the company.

For a better analysis of LCA or GHG impacts, Environmental Performance Indicators (EPI's) can be used. These group together inputs and outputs into categories to show a less detailed, overview report. Additionally, they sometimes only require certain environmental issues to be monitored, so reducing the overall effort involved. However, depending on the categories chosen, and the importance placed on each category, different outcomes occur, and because there is no regulated standard, these can be chosen arbitrarily to suit the conducting company [22]. Again they are based on static values and do not relate absolute values to the impact behind it [23], so no good comparison between different EPIs is possible.

However, the principle behind them is important and very valid – only by giving environmental impacts "meaning" by grouping them can the environmental footprint be visualised and explained to non-experts to allow a much better understanding of the importance of optimising the environmental footprint.

2.3 Detailed Analysis of Life Cycle Analysis

Whilst the GHGP offers a standardised accounting method for energy flows within the company, LCA offers a much more holistic approach to account for all inputs and outflows of a company or production facility, including different resources and emissions. Hence, it presents itself as a starting point for environmental optimisation. Especially after its regulation in ISO 14040 it has a much more structured system than the GHGP or EPI's. However, it is still up to the practitioner to interpret the required measurements and how to obtain the data.

"However, the standard [ISO 14040] regulates far from every methodological choice in an LCA. In fact, it allows for producing virtually any LCA result. And since the LCA methodology develops rapidly, the standard becomes outdated fairly quickly. As state-of-the art develops, guidelines and standards need to be adjusted" [16]

Pålsson [24] introduces one standard of how LCA data should be documented, based on the SPINE[1] format. She highlights that the interpretation of the data and the documentation by the practitioner should always be noted in addition to all measurement and modelling choices for maximum transparency.

Additionally, as described by Ong [25], the implementation of LCA requires end users of LCA to have in-depth knowledge of processes of all stages and good knowledge of environmental issues involved, but also indicates that this is not always possible in practice.

Azapagic [26] shows that, in order for LCA to benefit a company, there has to be an optimisation procedure used after the LCA is completed in order to determine where changes to the system should be made. The chosen methodology he proposes is multi-criteria decision making, which splits the LCA data into different impact categories, e.g. reserve and ozone depletion, and different production stages, e.g. mining and transportation. This allows for cross-identification of which production step should be optimised with respect to which impact category.

One problem with creating impact categories is that this generally involves weighting of impact and categories, as described by Ahlroth [27]. Depending on whether the

[1] SPINE format = Sustainable Product Information Network for the Environment, developed at Chalmers University, Sweden, in 1995

weighting is monetary (e.g. market prices, willingness to pay), or non-monetary (e.g. distance to target or panel weighting), different outcomes are found. Problems are found especially with respect to weighting in LCA, such as how to weight current and future emissions, or what cut-off points to establish for future emissions. Additionally, to show the effect of weighting, it is suggested that different weighting methods should be used in an LCA review to show their individual impact on the result. As a conclusion, it is noted that

"There is a need for generic sets of weights … Today, there is a lack of consistent weighting/valuation set" [27].

Andræ [28] shows through a review of LCA papers that

"there is a lack of representative component and material data for LCA purposes of electronic products, and it is also unclear if intermediate manufacturing processes are included in the results of the case studies", [28] which is also reflected further on in Section 2.5.9.

Different papers published relating to challenges in LCA implementation in industry and the different solutions offered are shown in Table 2-1.

Table 2-1: Selection of LCA Papers and their focus

AUTHOR	CONTENT
GENERAL LCA	
Ong (1999) [25]	Pre LCA environmental assessment tool
Guinee (2002) [15]	Introduction to LCA, approaches and methods
Andrae (2005) [28]	Review of LCA for electronic products
LCA WEIGHTING	
Kulkarni(2005) [29]	Weighting in environmental assessment methods, usage of different LCA packages (Eco-Indicator 95/99, EPS 2000)
Burrit (2006)[30]	Environmental Management Accounting, sub-classifications in management strategies
Ahlroth (2011) [27]	Weighting in environmental assessment, different LCA packages (EPS 2000, Eco-Indicator 95/99)
LCA AND OTHER METHODS	
Eagan (1997)[31]	Facility based Environmental Performance Indicators, introduction of different analysis systems (Green management assessment tool, Environmental self assessment program)
Pineda-Henson (2002) [32]	LCA and Analytic Hierarchy Process combination
Zopounidis (2002) [33]	Multi-Criteria Analysis in decision aiding
Benoit (2003) [34]	Applying Multi-Criteria Analysis to Environmental Assessment

Throughout the papers reviewed, four main methodological challenges were identified within the execution of LCA and other environmental standards.

1. There is a lack of *Transparency* in terms of data sources, data manipulation and regulation due to the limited documentation and advice provided in the standards.

2. The *Complexity* of the methodologies causes two problems: there is little short-term application potential and limited usefulness towards the factory operations. This also causes a reverse economy of scale – application to one product is manageable but application to different, complex factories and products becomes almost impossible with limited time and money resources.

3. Due to their top-level approach, data used in LCA assessments are mainly statistical, long-term averaged data. This *static approach* does not offer the dynamic optimisation potential needed to make factory loading dependent decisions.

4. The question of *ownership of environmental burdens* between the end-product producer and raw material sourcing companies can lead to miscounting or double counting of a material flow, and can hence introduce errors into both calculations.

Many papers [15, 35-37] focus on the business, or more specifically, on the product level or the factory, and not on the production processes [38]. This introduces more possibilities of inaccuracy, in terms of what emissions to count for which production site (for globally produced products), and how to account for local and regional impacts. A more detailed analysis of the four problems encountered can give a better understanding of what a practical solution for industrial purposes should look like.

2.3.1 Transparency

Transparency issues occur right from the start of an environmental assessment, starting with the setting of boundary conditions for the study, be it LCA or similar [35-37]. The choices made by the practitioner cause the results to be subjective rather than objective. Another factor is the clear indication of the functional unit [36], be it the product or company. This is identified in several papers [35-37]. Due to the lack of regulation there are few guidelines as what to exactly measure, and how [36, 37]:

"The criteria are stated, but means of satisfying them are not. The adopted methods for identification and assessment of environmental aspects can therefore differ considerably between different organisations. It is also difficult for an organisation to fully satisfy the specified requirements and to do this in a credited way, since guidelines for how this is accomplished are largely missing" [37].

Due to these inaccuracies identified in the guidelines, the data found and used is often of questionable quality and repeatability [39]. Even in the ISO 14000 series there is no guidance toward what is standardised and required for third party certification, meaning there is little reproducibility, clarity and comparability of the results [37]. Additionally Jasch [36] states:

"Which data should be collected to what scope and which methods should be used to evaluate these are not discuss either in EU- EMASS[1] regulation or in ISO 14031" [36].

2.3.2 Complexity of Methodology

Due to the methodologies like LCA being described quite broadly to fit a variety of industries and different company structures, the transparency required for a comparable, standardised result is not obtainable. Additionally, conducting these makes little financial sense to companies as there is no consumer reward for environmental stewardship, although consumer conscience is growing. They also do not allow for a quick adaptation of the factory to different products or loading without extensive re-modelling and optimisation. The complexity of the methodology impacts the ability for meaningful application of its findings.

[1] "The EU Eco-Management and Audit Scheme (EMAS) is a management tool for companies and other organisations to evaluate, report and improve their environmental performance." http://ec.europa.eu/environment/emas/index_en.htm

Additionally, the introduction of complexity from production sites and different products increases the workload almost exponentially. The execution is exhaustive for one product, but the more products, production tools and production sites are involved the smaller the chance are of applying one complex method to all of them. This introduces a problem with the economy of scale for the application: There has to be a much easier way to assess environmental impacts in a dynamic way in order for it to be used by companies, which will aid not only their own balance sheet but also put confidence in the consumer about the assessment.

Ekvall [16] describes in his review of the development of LCA the difficulty in obtaining the data necessary for LCA modelling:

"*If the LCA practitioner aims at describing the full consequences, the LCA model will always include data gaps and large uncertainties. … A modeller can aim at describing as much as possible of the consequences of an action, but it is not realistic to aim at describing the full consequences*" [16]

This again shows the problem of inclusion and exclusion of certain inputs and outputs, and demands a proper regulation for it.

2.3.3 Steady State vs. Dynamic Evaluation

As mentioned above, most existing environmental methods are largely based on top level, statistical static data [15]. This is due to usage of monthly or annual average values, which is mainly required in standards like ISO 14000 or PAS 2050, and due to the fact that there generally is no distinction between active and inactive phases in the factory. This plays into the top-down approach used, and is manifested in statements such as *"necessary data can be obtained from financial bookkeeping, production planning and controlling and production flow diagram."* [36]

For companies that are constantly producing (24/ 7/ 365), there is no provisioning for indicating the state of individual production components or areas. However, these can affect the overall steady state of the company. No consideration is given for production vs. idling phases and different consumption rates required between ramping up, idling, producing and ramping down.

2.3.4 Ownership of Environmental Burdens

One significant problem is the distribution of environmental burden ownership between resource supplier, manufacturer and product user. This manifests itself in two ways:

One way is that environmental regulations are fragmented and mainly focussing on one resource at a time. This means that different reduction efforts may negatively impact each other, and alleviating a problem at one point on the supply chain may cause much larger problems at another point in the chain.

"Reducing emissions that contribute to one environmental problem often lead to higher emissions contributing to another environmental problem" [23].

"However, the main disadvantage of these approaches is that they concentrate on the emissions from the plant without considering other stages in the life cycle. Thus it is possible for waste minimisation approaches to reduce the emissions from the plant but to increase the burdens elsewhere in the life cycle, so that overall environmental impacts are increased" [26]

The second problem with the reporting of upstream and downstream impacts is that emissions can be double counted, once by the actual producer and second by the consumer of that product, if both are conducting LCA's [40]. Hence, clear boundaries have to be established to ensure that no double counting occurs and that responsibility is split correctly. Additionally, this view leads to the consumer having 100% of the burden, as it is his requirement of the product that causes the production. Wiedmann [41] and others [42] suggest a 50/50 split of the responsibilities to avoid the total responsibility resting on the end consumer, with the companies not having any responsibilities at all. Companies should carry a considerable part of the responsibility as an incentive to reduce harmful emissions and to employ the most efficient and environmentally friendly production methods.

However, as described above, the resource consumptions are co-dependent, so reducing the volume of one may increase the other [43]. Therefore, it is necessary to weigh up reduction strategies with a view of all resources that are consumed, not just a single focus. As these co-dependencies are inherently dynamic, it is vital to take a dynamic optimisation approach rather than a static one. The environmental ownership between different resources can take place within a production tool, but can also occur factory wide, if for example, the environmental impact of a resource in the factory itself is mitigated, but the impact upstream or downstream of the factory is worsened. This can also be the case for entire nations. For example, with the Kyoto Protocol [44], the United Kingdom signed immediately, as their carbon footprint was below the stated percentage of 5% below the 1990 baseline [45]. However, industry in the U.K. is mainly focussed on parts assembly, leaving the environmental damage of sourcing and production in another country. Therefore, their carbon footprint is skewed, non-inclusive and missing the large footprint of raw material production areas [45].

2.4 Factory Design and Optimisation

Additional to the four methodological challenges outlined above, there are practical challenges to the implementation of environmental optimisation for production tools in the factories themselves. The layout of tools, support systems and resource distribution systems gives a baseline for the environmental optimisation as it restricts certain optimisation procedures.

Most factories have administrative and production processes. For complex manufacturing, this is again split into different parts:

- the actual production, for example in a cleanroom
- the support areas for this, for example housing pumps and power supplies and which produces specific consumables, such as chemicals, purified water and chilled water
- the building shell (i.e. outside and internal walls) of the building, and anything contained within the building shell, such as lighting or air conditioning

From a financial standpoint, previously there was no incentive to employ energy efficient building methods as often time to market and initial throughput of the factory was more important, and only with increasing regulation have more energy efficient building methods been used. Additionally, there was no incentive for retrofitting existing buildings, and there is still very little incentive to do so. Hence, energy efficient building strategies are mainly used in projects in the design phase, rather than for retrofitting the large number existing systems.

Due to vast improvements in building and manufacturing technology, newly built factories and systems can be very energy efficient with reduced running costs, where typically 40-90% savings can be achieved with a lower capital cost than existing conventional factories [46]. The main focus has therefore largely been on building shell improvement for new developments.

2.4.1 The Building Shell

The Leadership in Energy and Environmental Design (LEED) standard for new buildings [47] ensures an overall environmental optimisation, focussing, among others, on the sustainability of the site, the water and energy efficiency proposed and the emissions caused and their impact onto the local environment. It also includes positive influences to the building environment through ideas like white roofs and usage of plants for water treatment and irrigation. For Semiconductor Fabrication (fab) facilities, building standards such as LEED are fast becoming the norm and substantial savings have been made when designing fabs in accordance with LEED.

One example of this is the fab design process documented for the Texas Instruments RFAB [48], which was started to build in 2004 and opened in 2009. The challenge of having to reduce the overall building project cost per square foot by 30%, led to new innovative thinking and designing rather than the often adopted ‘Copy Exactly’ method [49] which is prevalent in the semiconductor manufacturing industry. LEED gives guidelines for topics to be addressed and solved, and hence is a good framework for reducing overall fab running energy cost. Specific to fab building, this means implementation of ideas such as:

- two temperature Process Cooling Water (PCW) loops as there are two distinct areas for usage with different optimum cooling temperatures

- usage of Flexible Fan Units (FFU) for the cleanroom, as there is only demand for air change if human interaction in that area is required, see also [50] as a study for energy reduction in demand controlled FFU cleanrooms.

The cost of the inclusion of LEED was less than 1% (= 1.5 M$) of the overall fab building cost, but the goal of 30% project cost reduction was achieved through it. With this reduction, 4M$ will be saved each year in the RFAB, thus recovering the LEED implementation cost in less than six months. The savings in the fab break down to 20% energy consumption reduction, 35% water reduction and a 50% reduction in emissions [48] in comparison to a previous Texas Instruments state of the art fab.

2.4.2 Within the Building Shell

Different strategies exist for optimisation of support systems and production tools, housed in the building shell. Again, these are focussed on the design phase and development of new factories, rather than on legacy (existing) ones. Focus is on the factory layout and the mitigation of by-products[1].

Whole system design [51] suggests new ways for factory equipment layout, and the efficient combination of it. Due to keeping the whole system in mind whilst purchasing or retrofitting, over-specification, through e.g. safety margins, is kept to a minimum and therefore avoids accumulative inefficiencies. This also includes, as an example, using bigger pipes with smaller pumps versus the industrial standard of small pipes with big pumps [52], also successfully demonstrated in the RFAB example above. Bigger pipes mean less friction, are cheaper than larger pumps and require less maintenance.

[1] By-products are defined as any undesired emission from the production step, other than the product. This includes usable co-products, emissions and wastes.

The Pollution Prevention Act [53] optimises production systems from the start, so that rather than having to use expensive waste collection and cleaning processes at the end of the production line, the cleanest methods are used within the production line/tool so that a minimum of waste and pollution occurs. This plays into the lean manufacturing movement.

The concept of Design for the Environment [54] evolved from this, by standardising the method by which environmental considerations are taken into account at the design stage of a product, tool or system, similar to the Design for Manufacture or Automation principles. However, this optimises each of the inputs and outputs in isolation, thus ignoring possible co-dependencies of them inside the factory, and negative impacts of them on each other.

2.4.3 End User Energy Efficiency

In heavy industries, and with the ever increasing complexity of their products, especially in sectors like semiconductor manufacturing or bio-technology, it is often that the production tools themselves consume most energy and resources and drive the consumption rates of the support systems, such as chemical production, and building systems, such as air conditioning. This is shown in Figure 2-5. The overall resource consumption and hence environmental footprint of the factory is much larger than the actual production tools footprint, though this is the only desired resource consumption area. Additionally, as safety margins are added at all stages [55], further inflation of the footprint occurs.

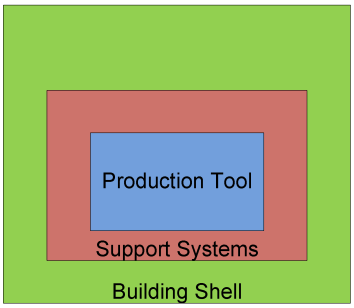

Figure 2-5: Relationship of production tool with factory

The obvious choice for short-term reduction is therefore to influence end user behaviour. This is especially important as it also immediately reduces the amount of resources required to be produced. As transmission losses are high and yields for the production of raw materials are quite low, any unit of resources saved at the end user can impact heavily onto the requirements at the sourcing point.

From Figure 2-6 it can be seen that around 90% [46] of usable energy is lost between the production of energy and the usage of it. This is mainly due to transmission losses, at 70%, and losses between converting energy, such as providing pumping power from electricity. However, these losses compounding down the supply chain can also be seen as savings compounding up the supply chain when one unit is saved at the end user.

These compounding savings mean that it is most vital that production tools, which are the intended end user of energy and resources in a factory, are optimised first, before optimising the surrounding support systems.

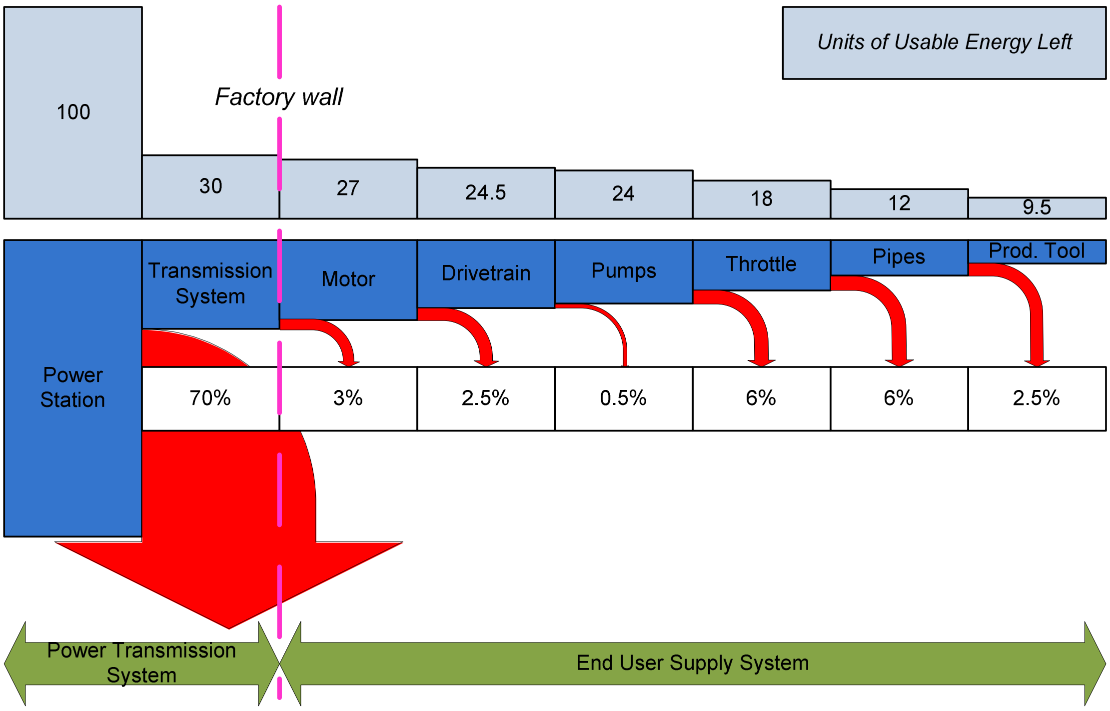

Figure 2-6: Energy losses within a power transmission and usage system, adapted from [46]

The production tools require a constant production environment, which in return require a constant support system and building shell. Therefore, if focussing on the optimisation of production tools first, the other systems can be optimised to a higher degree than if optimised in isolation.

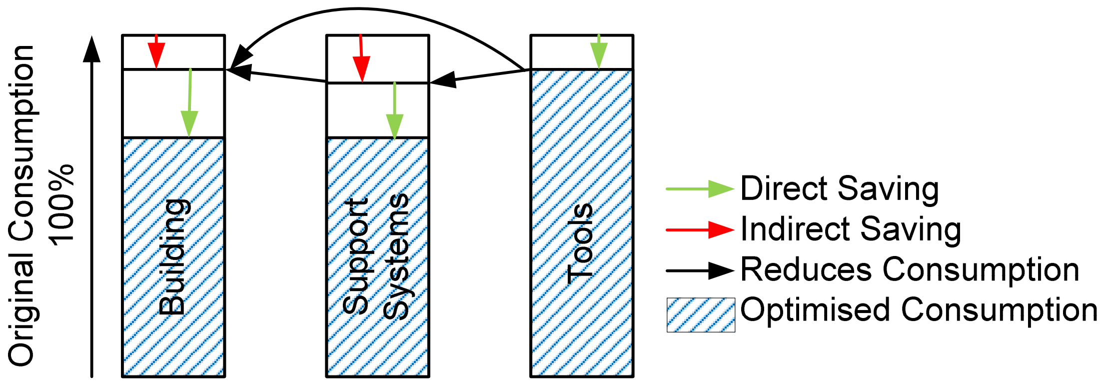

Figure 2-7: Direct and indirect consumption reduction in a factory

Figure 2-7 demonstrates this. If factory optimisation is started from the bottom with the production tool, not only are direct savings (green arrows) made at each step, but additional indirect savings (red arrows) are incurred by the reduction of the overall load on support systems and building systems before their subsequent direct optimisation.

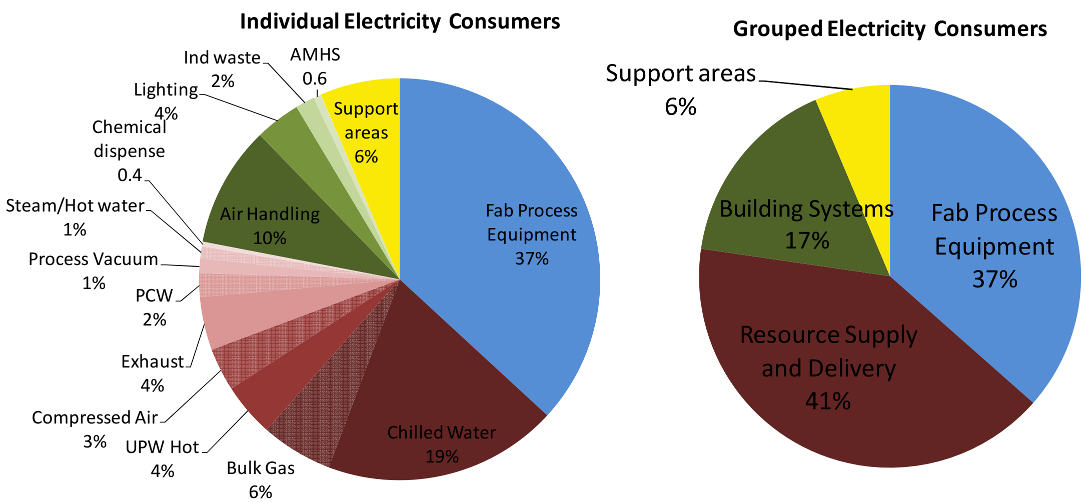

Figure 2-8: Electrical consumption within typical semiconductor factory, adapted from [56]

Studies in the semiconductor manufacturing industry have shown that production tools consume around 40% of the electrical consumption [56]. Additionally, they determine the size and components used in maintaining the production environment, resource conditioning and delivery, which again consume up to 40% [56] of the electricity. Both, production tools and environment, determine the size of building systems such as air conditioning and lighting, which constitute the remaining 20% of electrical consumption within the semiconductor factory, as shown in Figure 2-8.

The significance of compound savings is as follows: Currently there is very little possibility of reducing the losses in existing power plants as well as the actual transmission lines (70% loss). Hence, a focus on the consumer side is highly beneficial for short-term energy and resource reduction.

Research into optimisation of support systems and building systems has already been conducted, in the semiconductor manufacturing industry for example by cleanroom airflow optimisation [50]. But a focus on production tools themselves offers a unique opportunity of optimising not only the production tool itself but also reducing demand on all support systems and subsequently on the power station. This has not only environmental benefits but also large economical benefits as even within the factory walls consumption rates of various systems would be reduced. This has also been recognized by the European Union as a strategic goal [57], which lists end user efficiency as a tool for optimisation, not only in industry, but in every energy consuming field.

2.5 Case Study: Semiconductor Manufacturing Industry

The heavy industry sector is a prime target for environmental assessment and optimisation. The semiconductor manufacturing industry, although not heavy in terms of weight and volume of output product, is a modern heavy industry due to the amount of chemicals and energy required to produce one small product, of around $1cm^2$ surface area. This introduces the idea of *secondary materialisation* [58]: the impact and amount of resources used is not in proportion to the final product. The semiconductor manufacturing industry is a prime example as it is challenged with high purities and large volumes of supporting resources. Supporting resources here means that many are used to wash, clean or keep a stable production environment rather than actually being used up in the production sequence, to yield the final product.

2.5.1 Introduction to Semiconductor Manufacturing

Semiconductor manufacturing is defined by its highly complex manufacturing processes. This means that processes are hugely dependent on the production environment (temperature, humidity etc) and due to the miniature scale of the products in question, even the smallest impurity can destroy several microchips at once. A high number of repetitive steps to achieve layers of transistors on the silicon substrate (wafer) defines the product flow. This involves cleaning/oxidation of the substrate, implantation of chosen impurities for the transistors, photolithography, diffusion and etching, and with a high number of repetitions for each step. Each set of repetitions can be seen as a layer added to the final product. The more complex the product, the more layers are required. What is achieved is a wafer, currently of 300mm diameter, covered with microchips, which is then further processed into end products, mainly through testing and packaging. All these steps add up to 200-500 production steps per wafer, depending on the complexity of the product required. There is a varying number of yields on each wafer, which further complicates the production planning stages. Additionally, different layers require different amounts of time, meaning that a highly flexible production system is required.

The size of the transistors themselves has dramatically decreased over the past few decades, with Moore’s Law [59] governing their size. This again introduces more sensitivity to impurities and faults in the transistors themselves. Additionally, there has been an increase in the wafer size, to achieve better cost efficiency for each finished product. Currently 300mm wafers and fabs are the norm, with the next stage being 450mm wafers, which are already in development. Additionally, 200mm fabs are still used by many manufacturers, as the transition to 300mm was only started in 2000, and 200mm fabs are still producing products with a profit margin.

A cleanroom production environment is used to reduce the contamination risk. However, with increasing minimisation of the devices, control of manufacturing parameters and resources have to be even more precise, as well as consistent, to ensure a consistent product. Therefore a micro-environment additionally exists in the production tools themselves [60]. Newer production tools also have their own cleanroom environment inside to allow better contamination control.

Due to the complexity and sensitivity of the production processes involved, once a production tool is functioning, no change is introduced to the system. This is also founded in the Copy Exactly! Approach [49] used by e.g. Intel, which means that processes across the globe, once functioning, are copied across different locations.

2.5.2 Semiconductor Manufacturing Industry Organisations

Several different semiconductor manufacturing industry associations exist. Sematech (SEmiconductor MAnufacturing TECHnology), and its subsidiary, the International Sematech Manufacturing Initiative (ISMI), are a driving force in the future development of new technologies and the research involved with this. Similarly, the Semiconductor Equipment Association of Japan (SEAJ) and Semiconductor Equipment and Materials International (SEMI) are concerned with the development of the manufacturing equipment.

The International Technology Roadmap for Semiconductors (ITRS) [61] defines the direction into which Research and Development as well as production within semiconductor manufacturing should develop. This involves giving short- and long-term goals for all areas of manufacturing, such as metrology, yield enhancement and factory integration. One section that is gaining more and more importance is the Environment, Health and Safety section (EHS). Here, challenges faced by the industry as well as targets for e.g. chemical, water and electrical energy consumption are outlined and set. These values are seen as ideals to be aimed for and achieved by the industry, and are used as such in industry reports. For example, in a benchmarking study by ISMI in 2002 which compared fab energy consumptions, the ITRS value was used as an ideal to compare against.

2.5.3 Optimisation of Existing Support and Building Systems

In the past, a focus was placed on the reduction of the energy consumption of support systems, such as chillers. This was conceived as having less risk than changing patterns within the production tools. Many papers published with an industrial background only give general tips and problems related to energy in wafer fabs, such as heat load reduction and exhaust reduction [58, 62].

One study that actually provides data from their improvements is by Tower Semiconductor [63, 64], reviewing and optimising their existing chiller system. Steps like increasing the chilled water set point temperature and better management of chillers, by staging them according to demand rather than running them all at low efficiency, and additional heat recovery management lead to a 12% reduction of annual running costs with a very small investment of $20,000. This project shows that fab support systems can easily be retrofitted and updated to be much more energy efficient, with a minimum investment. It also emphasises that correct management of facilities is just as important as efficient systems themselves.

A publication by Tschudi [42] focuses on how state of the art new cleanroom developments can be energy efficient. Usage of demand controlled filtration and reduction of air circulation speeds saves around 70% of the overall cleanroom energy consumption. Both of these projects show that there is a huge potential for saving energy within the support and building systems of a fab, not only for newly build ones, but also offer considerable savings from retrofitting and optimising management of existing equipment.

2.5.4 Challenges in the Semiconductor Manufacturing Industry

The real challenge of resource efficiency improvements in industry is in legacy factories and systems, and the retrofitting of new, efficient components such as pumps or motors into these. However, the adaptation of new components is quite slow as they involve a capital investment. Therefore, currently existing machinery and plants are generally much older than the state of the art technology and are only replaced if entire factories are refreshed.

In the majority of cases, new components are fitted into supply and manufacturing systems that already have a determined layout with existing components and thus the concepts of Design for Environment or Whole System Optimisation cannot be followed fully, resulting into a less than perfect system, even if all or some of the components, in isolation, are state-of-the-art and energy efficient.

The Return On Investment (ROI) for the new components has to be very short, especially in factories whose products have a very short profit margin life cycle like the semiconductor manufacturing industry. Whereas most energy efficiency projects have a 2-3 year ROI [46], a lot of companies specify ROI to be less than one year in order to qualify for a retrofit [52]. Additionally the quality, quantity and general production of the product cannot be impaired. Any system improvements need to have net zero or positive impact on the production line or the final product, especially in terms of throughput.

2.5.4.1 Purity of Resources

The semiconductor manufacturing industry requires very high purities in their materials, which increases the off-site energy and resource consumption in the resource production. For example, to combine quartz and carbon into one kg of basic silicon takes 13kWh to produce. An additional 790kWh are needed in four production steps to process this into one kg of wafer grade silicon, with decreasing yields [58]. This steep increase in energy used for purification is representative for most resources required in the production process. Therefore, each resource has a very large existing environmental footprint before reaching the factory wall. Once within the factory, an additional footprint is created: Each resource needs to be stored, then brought to factory environmental specifications, i.e. to a set temperature and pressure with a stable flow, and then distributed to the actual production tools. This footprint varies in complexity for each resource.

In studies published so far the main focus has been on GHG data to determine the importance of each resource in energy and environmental accounting, e.g. [58]. But what is neglected are quantities of other resources e.g. water quantities consumed in the resource production, and the resource quantities used in the actual production.

2.5.4.2 Co-dependencies of Inputs and Outputs

In each production step, it is obvious that resource inputs form products and co-products (emissions, waste), for example in chemical reactions a mass balance will show this formation. However, what is often neglected is that the consumption rates of inputs are also co-dependent on each other. Hence, by optimising one input, not only outputs may be affected but also other inputs. Figure 2-9a) shows that, in order to optimise the overall environmental footprint, all inputs and outputs have to be viewed as co-dependent [65] and the aim of the reduction should be to minimise the area formed between the consumptions peaks, bearing in mind their co-dependencies.

Figure 2-9 b) shows how these co-dependencies can affect the optimisation process. The original focus in this example is to reduce the volume of PCW used. If no importance is placed on the other consumables, this would increase the electricity consumption, as shown in the dashed outline. However, with a holistic view the increased electricity load can be reduced by introducing passive cooling, hence reducing both points and truly optimising the tool, as represented by the smallest possible area and shown as the dotted outline in Figure 2-9 b) [43].

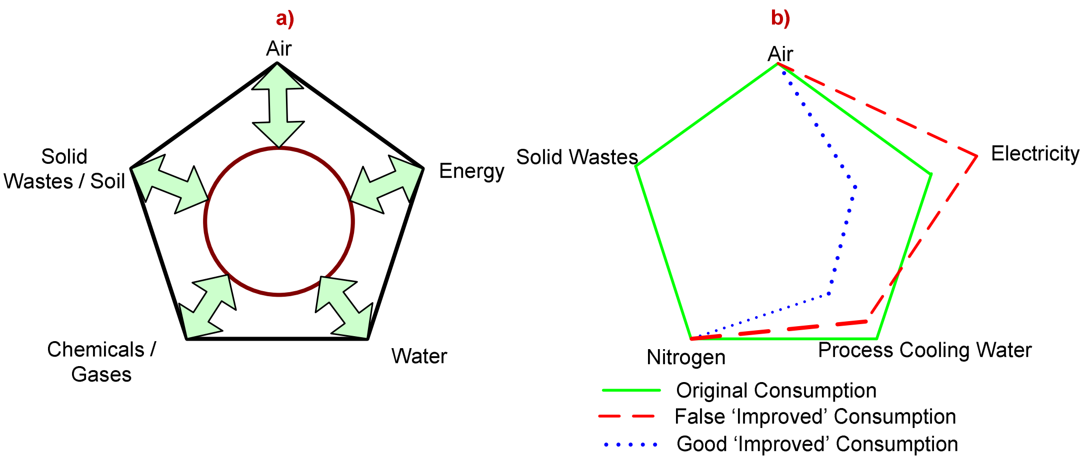

Figure 2-9: Consumable Relationships: a) Dependency of consumables onto each other b) Scenarios for PCW improvement, adapted from [43]

2.5.5 Consumption Patterns in Fabs

In the semiconductor manufacturing industry, consistent quality is the highest imperative and therefore most systems, such as pumps, or HVAC[1], and especially tools are *on* continuously to limit parameter changes occurring within the manufacturing facility. Switching *off* of production tools or support systems can introduce three undesirable outcomes and is hence often avoided: Due to complexity and stability issues in the fab, production tools could potentially not be returned to their original state, or

[1] HVAC = Heating, Ventilation, Air-Conditioning

the time to stabilise the system could take extensive amounts of time. Additionally purging of the tool supply lines can dislodge settled sediments in the resource supply lines, potentially causing problems in downstream tools or systems.

2.5.5.1 Overall Factory Consumption Pattern

This *always-on* state in the fab leads to an almost level energy consumption, as shown in Figure 2-10, so that although the production output varies by 50% over the measured time span, the energy consumption stays almost constant. Additionally, there are no seasonally dependent changes visible. Only the introduction of facility energy efficiency measures makes a difference in the absolute value of the consumption [66].

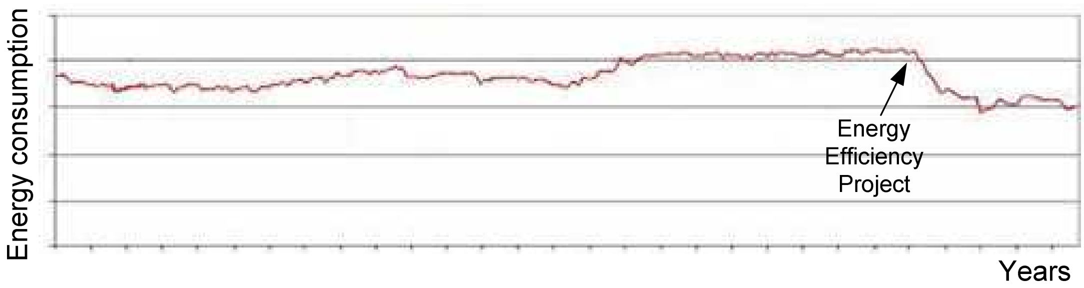

Figure 2-10: Typical fab energy consumption over time [66]

2.5.5.2 Production tool Consumption Pattern

The analysis of consumption pattern of production tools shows why their contribution towards the total energy consumption is so high. Even though no wafers are passing through the tool, the production tool environment is kept at a constant level of e.g. temperature or humidity. If these are varied, problems arise with the stability of the product, for example, small changes in temperature can majorly affect the actual production parameters such as layer thickness. Therefore, these parameters are very tightly controlled. This happens regardless of whether the tool is being used or is idle, and causes a very high idling consumption, between 75-100% of the production energy [67] and causing an almost constant energy draw.

A general pattern of the production tool consumption is shown in Figure 2-11. At point 1, the tool is maintaining the production environment, for example cooling and pumping. This environment is disturbed when a wafer enters the environment, as shown at point 2, which means extra energy is required to return it back to an environment fit for actual manufacture. Once actual manufacturing occurs, at point 3, very little additional energy is needed to actually produce. This shows that there is a large potential in the idling phase for reduction, especially in prolonged idling situations.

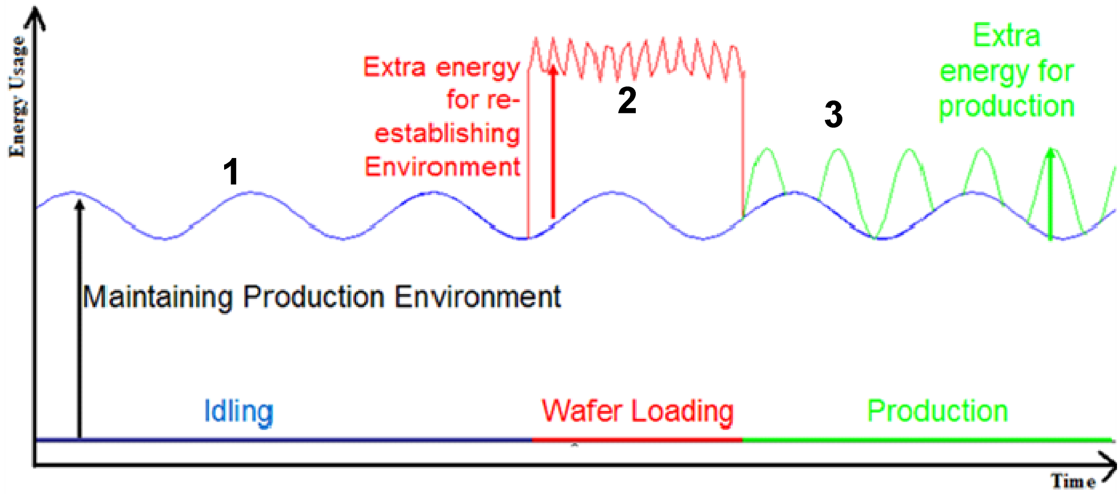

Figure 2-11: Typical production tool energy consumption pattern, adapted from [67]

2.5.6 Industry Studies for Energy Benchmarking

Energy data collected and published for the semiconductor manufacturing industry production is generally converted to a normalised energy consumption. There are two reasons for this: It allows publication of energy values without disclosing actual consumption values and it normalises against wafer sizes and production values of the factory.

For this calculation, the total factory energy consumption is divided by the total surface area of the wafers leaving the fab during the recording period:

$$Normalised\ Consumption = \frac{Energy\ Consumption\ [kWh]}{No\ of\ Wafers * Wafer\ Area\ [cm^2]} \qquad (2.1)$$

This formula yields a normalised consumption measured in kWh per cm^2 Silicon. This calculation might seem like a logical way for the comparison of different fabs, but in reality, it does not reflect the true energy required. Whilst it takes into account the electrical consumption, and hence includes production tools as well as support systems and building in its calculation, it completely neglects all other resources such as water, elemental gasses and chemicals consumption.

While it can be argued that electrical consumption is at least an indicative value for the overall properly foot printed consumption, and thus justifies usage of this formula, the formula neglects an equally important factor: It does not take into account the complexity of the product(s) manufactured during the measured time-span. Specifically, for the semiconductor manufacturing sector, this involves the number of the layers added to the wafer. Whilst some products can have a very low number of layers, many of the more complex products have over 20 different layers applied. Hence, if those two were compared on a purely kWh/cm^2 basis, the product with the lower number of layers would always be perceived as the more efficient product, however, if this number was normalised against the number of layers a different picture could be seen, and is demonstrated in Section 2.5.7.1.

2.5.6.1 *Electrical Consumption Data*

There has always been an interest in quantifying the energy footprint of a semiconductor manufacturing fab, and as early as 1997 benchmarking studies were conducted [56]. In these studies, systems were placed into groups to show the overall consumption of each functional sector, such as support areas or processing tools. In a study conducted by ISMI in 2001 these groups were even more detailed to allow a more comprehensive electrical consumption breakdown [56]. From the data an average electrical consumption allocation was developed, similar to the ones found by an Asian industry study, conducted by Hu and Chuah in 1999 [68]. Figure 2-12 shows, as a first, a best fit comparison between the data from the 2001 ISMI study [56] and the study by Hu [68], allowing for overlap between groups as well as a mismatch between certain categories.

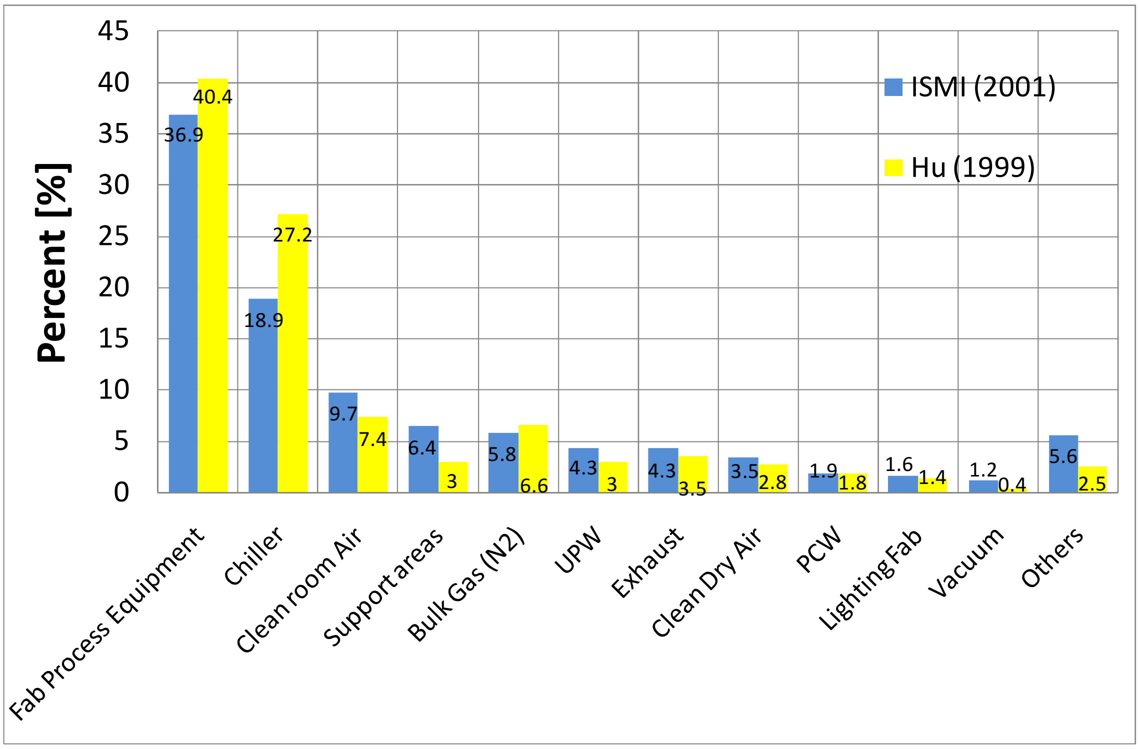

Figure 2-12: Average electrical consumption by consumer, data from [56] and [68]

It can be seen that, generally speaking, there is a good match between the categories, for example processing tools are around 40%. These figures also show that the order of consumer groups did not change over the timeframe of five years. Although there is some difference in the rankings of categories, this is most likely due to the category definition, which is especially predominant for the ‘Others’ category.

However, these percentages give no indication as to whether the actual amount of energy has been reduced over the timeframe. Looking at the daily electrical consumption reported in both studies, values of 349k kWh/day in 1999 and 522k kWh/day in 2001 are given. These values indicate that overall energy consumption has not reduced, but has rather increased. Possible reasons for this could be difference in products, increase in product complexities and different geographical locations. Another factor is that this is a comparison between relatively old technology - 100, 150 and 200mm fabs in Hu - and state of the art technology - 200mm fabs in ISMI study. Therefore an increase of 50% could be natural due to increased wafer size, similar to the projected 1.5 times increase in the 200 to 300 mm transformation given in the 2001 Semiconductor Roadmap (ITRS) [69].

In the ISMI study, the average value for the electrical energy per wafer area is 1.59kWh/cm^2. From the 2001 ITRS [70] the projected value should be larger than 1.4 kWh/cm^2, to account for additional systems not included in previous ITRS editions. This places the average obtained by ISMI close to the ITRS value. However, the significance of the average is reduced when looking at the range of the data found, from 0.65 to 2.54 kWh/cm^2, with eight out of 14 tested fabs scoring over 1.65 kWh/cm^2. This again highlights the need for an inclusion of different factors such as complexity into the consumption rates to obtain a true representation of the fabs efficiencies. Due to confidentiality issues, these kWh/cm^2 values cannot be retraced to actual consumption per cleanroom area and/or total energy consumption. Similar to the non-conformance of the overall energy per cm^2 values to the ITRS, the tool and facilities targets are also not met. With an average of $1.27kWh/cm^2$ for the tool data instead of $0.5kWh/cm^2$ and an even higher value of 2.56 kWh/cm^2 for the facilities data compared to the 0.5-0.7 kWh/cm^2 guideline, it is clear that a lot of work is needed for the ideal ITRS value and reality to coincide.

2.5.7 Discussion of Academic Papers

Only a small number of academic papers were found that deal with the topic of energy consumption in the semiconductor manufacturing industry. Of these, very few contain actual specific data but rather suggest general ideas for energy efficiency reduction such as cleanroom issues and facilities systems similar to the industrial ones.

One reason for this is the sensitivity of data required for detailed studies. The industry is driven by ever decreasing chip sizes and very complex, tightly controlled processes producing them. Thus, the publication of any even remotely sensitive data could lead to copying of processes and consequently reduction of profit margins. Hence, there is a distinctive lack of comparable and usable data within the values published.

Most of the documents found only provide an overview of possible energy reduction projects without validation of its costs and benefits. They generally show the problems encountered rather than offering concrete solutions or analysis of them. Additionally they focus on new fabs or new support systems. One of those papers is [62], which focuses on redesign strategies of legacy facility systems and cleanrooms.

One of the first documents to show the importance of energy efficiency in semiconductor manufacturing was published by the Pacific Northwest Pollution Prevention Resource Center in 1999 [14]. It focuses on the general problems of energy waste in a fab and hurdles encountered in removing them. This study also finds that energy is an important factor in the industry, and although estimated to be only 1-2% of the overall cost of the product, it is set to rise with consumable and utility costs. This document, as the sole document to do so, sets the energy consumption of a fab into a general context as being *–"enough to power a small city"* [14]. This in return again shows the significance of saving energy within a fab: One saving here is equivalent to every household in a town making significant changes to their energy consumption. In contrast to this there are many low hanging 'energy' fruit in a fab, which are not only easy to implement and have significant environmental benefits, but also make sense from a financial viewpoint.

2.5.7.1 Summary and Discussion of Findings

A summary of data that supply and investigate the overall energy consumption data of a fab is shown in Table 2-2. The data samples span almost a decade and cover three different wafer sizes (150, 200 and 300mm). Some contain a mix of products [68, 71, 72] and some are collected for specific products [58, 73, 74]. It is expected that the data for specific products should be more reliable, as the factor of varying layer numbers and/or products is taken out of the calculations.

Table 2-2: Comparison of energy consumption data within selected fabs, adapted from sources [58, 68, 71-74]

	Williams [58]	Hu [68]	Deng [71]	Williamson [72]	Boyd [73]	Taiariol [74]
Year of study	2002	2003	2005	1997	2006	2001
Basis for calculations	32MB DRAM [1]	Six Taiwanese fabs [2]	total US el. consumption	Average of 12 US fabs	CMOS [3]	1MB EEPROM [4]
Wafer size [mm]	200	200	-	150 / 200	300	150
Yield per wafer	75	-	80	-	80	-
Chip area	1.6	-	-	-	1.21	-
(average) Number of layers	-	20	-	-	6/8	21
(average) Wafer starts per year 000s	-	370	-	20	-	-
Average electrical consumption [kWh/cm^2]	1.5	1.43	1.5	1.045	1.29 [5] 1.55 [6] 2.89 [7]	0.66 [8]
Total Front end electrical consumption [MJ]	27	-	-	-	-	2.39
Assembly electrical consumption [MJ]	5.8	-	-	-	-	10.11[9]
Water [l/chip]	32	-	-	-	410 PCW [10]	29 [11]
N_2 [gram/chip]	704	-	-	-	0.003	122
O_2 [gram/chip]	4.8	-	-	-	-	0.14
H_2 [gram/chip]	0.07	-	-	-	-	0.029

[1] DRAM = Dynamic Random Access Memory, stores data but needs constant refreshment in order to keep data
[2] (average) of subset of 200 mm wafers chosen from original data
[3] CMOS = Complementary Metal Oxide Semiconductor, type of IC used in many different computing parts such as microprocessors or random access memory
[4] EEPROM = Electrically Erasable Programmable Read-Only Memory, stores non volatile information and keeps data even if power is off
[5] 6 layer 300mm wafer
[6] 8 layer 300mm wafer
[7] 6 layer 200mm wafer
[8] kWh/chip, Front end only
[9] Backend Consumption
[10] for one USG CVD processing step
[11] value for Distilled water only

Of these six papers, the average electrical consumption per cm^2 of Silicon [kWh/cm^2] value is available for five of them. When investigating these values in more detail, it becomes apparent that the values do not vary greatly between 1997 [72] and 2006 [73]. The values also do not seem to be affected by wafer size or number of layers applied, where provided. This confirms the assumption from earlier that this measure is not indicative of the actual energy consumed on a per-chip or per area basis. In addition, some of these values could have included previous stages, such as energy consumption in silicon procurement, into their calculations, thus possibly distorting the results. This is a major problem with most of the data presented: The boundaries and what is included and excluded is often not clearly stated, thus reducing the reliability of the data.

When removing the influence of layers in the equations the difference in the actual per layer data and the lack of comparability becomes even more apparent. Only two studies give values for kWh/cm^2 and number of layers, Hu [68] and Boyd [73], and the calculations are shown in Table 2-3:

Table 2-3: Comparison of kWh/cm^2 of Layer of different sources

Source	Wafer Size [mm]	Energy per cm^2 Silicon [kWh/cm^2]	Number of Layers applied	kWh/cm^2 of Layer applied
Hu et al [68]	200	1.43	20	0.07
Boyd et al [73]	200	2.89	6	0.48
	300	1.29	6	0.22
	300	1.55	8	0.19

There is little difference in the kWh/cm^2 value, although they are from two different technology generations, only the Boyd 200mm data is distinctively different. When dividing this by the number of layers, it becomes clear that kWh/cm^2 is not indicative of the energy consumption in a semiconductor product at all. One factor in the discrepancies could be that Hu’s data is an average value obtained from different fabs whilst Boyd’s specifically deals with one product.

2.5.8 Application of Different Normalisation Methodologies

Two more factors that influence the perceived energy used are discussed in the literature. One normalised the energy consumed to the area of cleanroom it supports, and the other introduces the number of layers applied to the wafer as a factor.

Table 2-4: Ranking of fabs - total fab el. consumption vs. total el. consumption per cleanroom area, from [56]

Rank	**Low Value**					**→**					**High Value**		
Total kWh el. consumption by fab	A	B	C	D	E	F	G	H	I	J	K	L	M
Total fab el. consumption by cleanroom area	D	B	K	H	C	E	G	L	I	J	F	M	A

Table 2-4 shows the energy consumed by Fab A-M per total fab consumption and energy per cleanroom area. It shows that although the overall electrical consumption might be lowest, in this case Fab A, if it is related to the cleanroom size, and hence indirectly to the number of tools and size of support systems in the Fab, it suddenly is the worst performing Fab. Only Fab B stays as a truly efficient fab in both measures. Fabs G, I and J also stay in the same position of ranking, whilst all other fabs change between efficient in one measure and inefficient in the other, with A, C, E and F becoming less efficient and Fabs K, H and L becoming more efficient.

Similarly, the importance of complexity becomes apparent if comparing the rankings of fabs with respect to kWh per cm^2 and kWh per Unit of Production (UoP). The definition of kWh per UoP is [56, 68]:

$$[kWh/UoP] = \frac{Electricity\ Consumption}{Annual\ Wafer\ Starts * Wafer\ Area * Number\ of\ Layers} \qquad (2.2)$$

The difference of introducing the number of layers is shown in the first two lines in Table 2-5. Whilst the per Silicon area values range from 0.65 to 8.68 kWh/cm^2, the addition of complexity brings the values to range between 0.03 and 0.36kWh/UoP, therefore bringing the range of values much closer together. Due to confidentiality issues, fabs A-M from Table 2-4 cannot be related to FAB 1-14 so no correlation between UoP and Cleanroom efficiency can be made. Additionally, it shows that layers alone have little influence on the energy, as the order of fabs does not change significantly, only two fabs (7 and 11) move significantly. A similar effect can be seen in data from Hu [68], where again both values are used, shown in two last lines in Table 2-5. Again, very little change is observed in the positions of the fabs.

Table 2-5: Comparison of electricity consumption per cm^2 Silicon and per Unit of production, from [56, 68]

Study	**Unit**	**Low Consumption**													**High Consumption**
ISMI study [56]	kWh/cm^2	3	8	2	1	7	5	14	6	12	9	10	11	4	13
	kWh/UoP	3	2	8	1	7	5	6	14	12	9	4	10	11	13
Hu study [68]	kWh/cm^2	I	E	C	H	G	D	B	F	A					
	kWh/UoP	I	D	E	C	H	G	F	B	A					

Another measure introduced in the literature, by Deng [71], is '*energy intensity*'.

$$ET = \left(\frac{EC}{WS * WA} * \frac{DS}{Yield}\right)/NT \qquad (2.3)$$

Where

EC = total energy consumption of the fab
WS = wafer starts per year
WA = wafer area
DS = die size of a CPU
Yield = die yield
NT = number of transistors on one CPU

This formula takes into account yield and die size, and thus shows a more detailed picture of the energy consumption per unit. However, the complexity of the product is still not taken into account. This formula is more relevant to production throughput than energy consumption classification.

2.5.9 Challenges Identified from Publications

One problem found with all these publications is the fact that the term *energy consumption* is not defined specifically. Thus, it is unclear whether purely electrical energy is included, or if it is a combination of different energy sources.

After a more detailed review of the actual data in each, it becomes quite clear that there is no convention with respect to which units should be used and what data should be reported. Sometimes the data supplied allowed conversion, e.g. kWh/chip and chip size give kWh/cm^2, but mostly this was not possible. This can be seen in the Taiariol [74] study, where a basic analysis as well as very detailed values are given, but these cannot be compared to the others as they are on a per chip rather than per cm^2 basis. The inherent problem is that without a proper definition of which data should be measured in which unit and presented in a report, results will never be on the same level. This uncovers an even deeper problem, as definitions for how to measure each value vary wildly between all the sources. This covers boundaries, starting points for LCI's and even starting values for overall energy consumption, e.g. Deng [71] vs. Taiariol [74] where one takes the total amount of energy used by the entire Northern American semiconductor manufacturing industry and the other is specific for one fab only. All of this reduces the reproducibility of the data as well as reducing the confidence into the values presented. The only dataset which can be certain to be on the same basis are the three values for Boyd [73], as these were calculated in exactly the same way.

Another problem with the data provided is the problem of comparing and including the impact of the chemicals and gas data supplied. There is a limited way of comparing their environmental impact by converting some of their values using GHG equivalents. However, this does not give an account of all the energy that went into the consumables production, but rather the ‘after’ effect of them onto the environment. Due to the high purities required, the energy consumed to ensure this is very high, as described in Section 2.5.4.1. Hence, simply using the purchase price of e.g. an elemental gas is not enough to describe its full environmental impact. The energy and resources required for purification, transport and within fab walls needs to be included, e.g. energy used in pumping, keeping up stable flows as well as controlling pressures and temperatures. Only this could provide a full environmental impact assessment.

There are three studies that not only take the electrical energy consumed into account, but also try to quantify the amount of water and elemental gasses consumed. Williams [58] and Taiariol [74] focus on a per chip basis and Boyd [73] focuses onto a per processing step basis. As a result, the Boyd Paper cannot be compared directly to the other two, and for a more detailed comparison only Williams and Taiariol [58, 74] are used. Whilst both use LCA as their base methodology, different definitions and starting points are used, hence giving doubt about the comparability. Their results for water consumption are both around 30 kg, but the results for electrical consumption vary by a factor greater than three, as shown above in Table 2-2.

There are two possible reasons for the difference in electrical consumption: Due to different wafer sizes, the energy consumption could differ. Taiariol [74] used 150mm wafers, but Williams [58] does not include its wafer size, however it is mentioned as ‘state-of-the-art’ and thus presumably uses 200mm or even 300mm wafers. Even a technology generation difference could not explain this difference. Neither study mentions or shows the use of production factors such as idling times and idling energy consumption, wafer throughput or, the number of layers applied, all of which could majorly affect the overall consumption value.

2.6 Industry Guidelines Offered

From an industrial viewpoint, there are many published guidelines with the aim of establishing baseline energy and utility consumption rates for semiconductor manufacturing equipment. They have been published by Western [75] as well as Asian industry associations [76] and follow the same scheme: A template is developed that allows easy calculation of annual utility consumption with a focus on electrical consumption. All of them are based on a document published by SEAJ named "Guidelines for Energy Quantification on Semiconductor Manufacturing Equipment and Utilities" [76].

2.6.1 Industry Association Guidelines and Production Tool Consumption Reduction

The SEAJ guideline for Production Tools and Utilities [76], introduced in 2003, was first to establish baseline practices for energy and resource management on production tools. As a first, it also introduces different production modes, such as idling and the inclusion of their respective resource consumptions.

The main selling point of this work is the fact that, for the first time, Energy Conversion Factors (ECF) are used for all resources to convert them to kWh equivalents, hence enabling the comparison of different utilities on a common ground. This means that suddenly the scale of consumption rates becomes much more apparent: A very small Ultra Pure Water (UPW) volume has a much larger kWh equivalent than a very large volume of exhaust. The calculation of ECFs for some consumables is shown in Table 2-6. This shows that the energy required for exhaust or vacuum generation is very low

(>0.075kWh/m^3), whilst production of Ultra Pure Water (UPW) is the highest at 10.2 kWh/m^3, which is tenfold more than the generation of low temperature cooling at 1.78kWh/m^3.

Table 2-6: Energy conversion factors, from [75]

Utility or Material		Energy conversion factor (ECF)	Basis of ECF
Electricity		1*V_{RMS}*I_{RMS}*measurement period = kWh	Electrical energy supplied. Not the same as energy used to generate the electricity
Water	**Cooling Water (20-25C)**	1.78 kWh/m^3	Water cooled by refrigeration process Supply pressure: 4.9*10^5 Pa
	Cooling Water 32-37C)	0.25 kWh/m^3	Water cooled by open cooling tower Supply pressure: 4.9*10^5 Pa
	UPW/DIW (under pressure)	10.2 kWh/m^3	Supply Pressure: 19.5*10^4 Pa
	UPW/DIW ambient pressure)	10 kWh/m^3	Power for distilling
Bulk Gas	**Dry Air**	0.147 kWh/m^3	Supply Pressure: 4.9*10^5 Pa
	Nitrogen	0.25 kWh/m^3	Supply Pressure: 7.93*10^5 Pa
Heat Load	**Removal via Air**	3.24*10-4 kWh/m^3C	specific heat and density of air
	Removal via Water	1.16 kWh/m^3C	specific heat and density of water
	Burden (Radiation)	0.382 kWh/kWh	refrigeration (air conditioning) efficiency
Exhaust		0.004 kWh/m^3	Exhaust pressure: 2 kPA
Vacuum		0.075 kWh/m^3	Vacuum Pressure: 58.8*10^2 PA

The ECFs were adapted and used in the SEMI S23 guideline [75], which again is concerned about the conservation of all consumables used in a production tool. It also adds values for Nitrogen and heat load, which was only included as radiation in the SEAJ standard. The S23 conversion factors and utilities covered can be seen in Table 2-6. S23 shows more detailed calculations for the ECF's, and e.g. takes into consideration different pumping factors for the electrical calculations for gas and fluid values, as shown in Table 2-7.

Table 2-7: Calculation of ECF for exhaust air, from [64]

Exhaust air						
Assumptions:	Shown not including and also including energy for makeup air to replace exhaust (this is in range of US$ 3 - US$ 5 per cfm/year from prior studies)					
At	0.065	per kwh, would be	46.15385	to	76.92307692	kwh/cfm/year
	Converting to hourly basis and m3 =		0.003101	to	0.005168452	kwh/m3
Point of connection negative pressure available =				500	Pascal	If greater than -500 Pa needed, calc will add
Static pressure at fan suction =				-1500	Pascal	
Static pressure at fan discharge =				250	Pascal	
Typical VP at fan discharge =		[add formula for VP…]		139.33	Pascal (assume 15.23 meter/sec)	
Total pressure across fan = TSP + VPd				1891.73	Pascal	
N.B. -- Different types of exhaust have different system TSP						
Fan efficiency =				0.65		
Motor efficiency =				0.88		
Calculation:		per 1 M^3/hour				
=	0.00092	factor	excluding makeup air			
or						
=	0.00402	factor	INCLUDING MAKEUP AIR (SAME AS S23 ASSUMPTION)			

The inclusion of the basis for the ECF calculation also shows one of the limitations of the ECF's: If the exact criteria are not met, the values obtained will be less precise. However, as said in the S23 guideline:

"*the actual electrical energy required to provide a particular utility … will… vary among locations… if a reasonable set of conversion factors are used, the output of the conversion can be used to identify those utilities and materials which, generally speaking, have a higher environmental impact*". [75]

2.6.2 Total Equivalent Energy tool

One solution to this is the introduction of self-derived, factory specific ECF's, which are given in the Total Equivalent Energy (TEE) Tool [77]. This TEE tool is a recording facility for the S23 guideline, to facilitate the capturing of consumption data of legacy production tools. A screenshot of the TEE tool can be found in Figure 2-13. This matrix for the first time, showed what exactly was to be measured and what effort was involved in obtaining this detail. The consumption for each consumable is measured for each subcomponent of the tool, such as environmental chambers, steppers or UV light sources.

TEE User Tool

1: TEE Tool Home | 2: Tool Editor | 3: TEE Report | 4: Tool Comparison | 5: Energy Conversion Factors

Annual Utility Energy Consumption by Component

Name: Environmental Chamber

Utility	Item	Conversion Factor (kWh/m3)	Amount of use (M3/h)	Real Power (kWh/h)	Annual Electric Energy (kWh/Year)	Subtotal (kWh/Year)
Vacuum	Processing	0.075	0.0	0.00	0	0
	Idle		0.0	0.00	0	
Exhaust	Processing	0.004	849.5	3.40	23,827	28,278
	Idle		849.5	3.40	4,468	
Nitrogen	Processing	0.25	0.0	0.00	0	0
	Idle		0.0	0.00	0	
Dry Air	Processing	0.147	0.0	0.00	0	0
	Idle		0.0	0.00	0	
High Pressure Dry Air	Processing	0.175	0.0	0.00	0	0
	Idle		0.0	0.00	0	
PCW 20C - 25C	Processing	1.78	1.4	2.49	17,450	20,186
	Idle		1.4	2.49	3,272	
PCW 32C - 37C	Processing	0.25	0.0	0.00	0	0
	Idle		0.0	0.00	0	
UPW	Processing	10.2	0.0	0.00	0	0
	Idle		0.0	0.00	0	
Hot UPW	Processing	92.2	0.0	0.00	0	0
	Idle		0.0	0.00	0	
			Mean Real Power kWh/Yr	Processing	49,056	58,254
				Idle	9,198	

Figure 2-13: TEE tool Screenshot: Reporting consumptions from one Component, from [77]

Another document, published by ISMI in 2002 [78] describes EHS metrics that were considered to develop a comprehensive EHS model of a manufacturing tool. It is accompanied by a table describing how they should be measured, although it is acknowledged that the measurement procedures should be standardised. A similar effort can be found in the SEAJ document [79], where a total testing document is laid out for calculations of equivalent energies and measurement data.

However, the SEAJ and the S23 guideline were developed mainly for next generation tools, and are not easily transferable to existing legacy tools. For this, the TEE tool was developed by ISMI and SEMI: it gave a direct framework for the measurement of all utilities as well as an easy matrix to enter values.

The practical execution of this is quite difficult, as there are many small pipes with very small flows through them that are hard to access and measure, and there are very few installed flow meters on production tools [66]. Again, an actual description of how the measurements are to be conducted and which equipment to use are not given. A document by ISMI [80] is the first to describe actual measurement methods and gives solid advice on how to approach them.

One problem with the SEAJ and the S23/TEE tool is that not all ‘energy’ that is needed in the fab is actually included in the calculations. For example, wastes are not included, yet would have a rather large kWh equivalent.

It can be said that the effort from the two guidelines is a good starting point, however there is a need for improvement. This covers the setting of a limit of how much detail is required (i.e. what flows below a certain threshold to ignore for each consumable) as well as including neglected influences such as waste disposal. Only then would a complete LCA be possible that weighs up the inclusion of all sizes of utility consumption with creating a picture that captures the majority (~80%) of the total consumption.

2.7 Conclusions from Literature Review:

From the academic and industrial publications reviewed, it becomes clear that there is a need to focus on the demand side reduction within the factories, starting with production tool optimisation. This should include not only energy consumption but also all other consumables supplied to them.

Even though existing methodologies offer optimisation potential, there are several issues that hamper comparison of different studies conducted with the same principle and the uptake of environmental assessments and optimisation strategies within companies. The main issues are as follows:

1. The complexity and requirements of existing methods in terms of data acquisition is generally too high, whilst offering little optimisation potential. Additionally, production tool assessment methods and regulations only exist for new production equipment, whilst there are predominantly existing tools used in factories.

2. The issues of transparency, standardisation and inclusion of upstream and downstream environmental impacts are generally not addressed, and hence allow easy manipulation of the results, sometimes to the advantage of the factory.

3. The definition of a common measurement unit is crucial in allowing a normalised comparison of different consumables. The units investigated such as the kWh/cm^2 Silicon measure shows that there is a need for a more significant unit. Whilst ECFs are a good starting point for this normalised comparison, they

should be extended to include consumables other than electricity in the calculations for a holistic approach rather than just focussing on energy.

4. The usage of static data such as annual consumption averages does little to encourage environmental assessment uptake since it does not give tangible areas for optimisation and hence offers little gain, financial or knowledge wise, to the company as an incentive.

Chapter 3 Investigation of Online and Offline Production Tools

3.1 Introduction

In the literature review it was determined that steady state data as well as averages of consumption rates are prevalently used in assessing environmental impacts. Additionally, most methods were based on product environmental impacts [81], and hence offer little incentive to the manufacturer to implement them, as they offer very little benefit to the manufacturer.

However, it was also shown that the production tools in a complex manufacturing factory are the major factor in driving consumable volumes, thus offering themselves as a focussing point for determining environmental impacts. This solves several problems: First, if measuring direct tool consumptions, the dynamic behaviour is captured, which provides a much better overview of the different volumes used at different production stages. Second, this offers direct optimisation potential to the factory owner since the consumption volumes are known. Third, as a by-product of a production tool assessment, the partial impact of the product is found, and if all tools are assessed, the total product impact is provided.

To evaluate the benefits and practicality of the proposed new environmental assessment methodology, dynamic consumption data was thus required. Two different tools were investigated in detail. One was located in the industrial partner's fab, and one in the university. The online semiconductor manufacturing tool evaluation showed the complexity of the inside of the tool and the vast amount of support systems to a complex production tool, and highlighted issues associated with real factory data gathering. The offline laser-cutting tool proved the application of the methodology and data acquisition in an easier to access tool.

3.2 Complex Industrial Manufacturing Tool (Online)

The semiconductor manufacturing industry has several advantages that mean it can quickly adapt to new methodologies. It has quite condensed product cycles, so that consumption values of production tools are changed frequently. Due to its involvement with lean manufacturing, a mindset exists where continuous improvement of systems is encouraged and the integration of environmental assessment methods as a tool for waste minimisation could occur easily.

By learning the working and behaviour of the factory and engaging full time with the energy reduction and utility provision groups at the early stages of the research, many different challenges were identified. During interaction with the employees, most of these were highlighted and practices suggested in literature were quickly analysed in terms of application and problems. This for example included the decision making paths as well as the sharing of information between different departments, which showed that there is need for better communication.

After discovering the TEE tool and introducing it into the factory energy focus group, a factory floor wide rollout was attempted. The outcome of this gave vital information to this research:

The *granularity* of consumable supply monitoring systems ended in each bay and chase[1] combination in the cleanroom. This means that, because there are several tools, and

[1] The cleanroom is divided into pairs of bays and chases. The front of a production tool (where the wafers are loaded) is located in the bay, where clean air is drawn downwards through laminar flow air supplies to

sometimes different tool fleets in each bay and chase, individual production tool consumptions cannot be determined. Similarly, in the factory accounting systems, only consumption values for major distribution points were found.

There is *limited existing instrumentation* on the legacy tools. If instruments do exist on the production tool they are very often visual gauges and are often only monitoring the pressure rather than the flow of the consumable. Hence, these are unsuitable for constant measurement and management as well as the establishment of an environmental footprint. This problem was encountered by most tool owners whilst populating the TEE tool, as well as during various tool evaluations by the author. Only chemicals used in the process itself are micro-managed and their consumption recorded.

The *addition of new, intrusive measurement devices* for flow measurement, temporary or permanent, is extremely complicated, if not impossible. Due to contamination issues only certain devices are allowed, and new ones require a lengthy qualification test period before employment. Their installation is very hindered as most tools run 24/7 and hence have no downtime for installation. Additionally, fears of dead-leg sediments dislodging and blocking up or downstream tools are extremely high. Therefore, non-intrusive measurement methods like ultrasonic flow meters are favoured and often required. However they pose a challenge in themselves as they are often designed for large pipe diameters, as Ultrasonic fluid and gas measurement deteriorates with smaller pipe sizes [82]. Hence, the required small diameters combined with small flow measurements that exist in the factory and which the TEE tool requires, cannot be measured. For example the Panasonic Ultrasonic gas flow meter, used by the test site, can only measure flows in pipes larger than 3 inches in diameter [83]. Electricity

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minimise contamination issues. The chase contains the actual production tool as well as its control equipment and consumable supplies, and airflow is more turbulent, thus contamination threat is higher but the equipment is less crucial.

consumption is comparatively easy to measure with clamp-on power sensors on switchboards, is mainly non-intrusive and was successfully measured for many tools.

Additionally, as already described in Section 2.6.2 due do the *complexity* of requirements in the TEE tool, the measurement effort is quite high, requiring many man-hours for one tool. If this requirement is multiplied by e.g. ten tools in each bay-chase combination, and each cleanroom consists of many of them, the measurement effort becomes overwhelming and is not suitable for an entire factory floor. However, the TEE tool is only useful if tools of the same fleet can be compared and then all tuned down to the lowest levels recorded. Yet, as demonstrated above, to obtain all necessary data from all tools across all fleets is virtually impossible.

3.2.1 Semiconductor Manufacturing Production Tool Preliminary Analysis

Semiconductor manufacturing industry tools are often multi-chamber, multi-action tools, and an example is shown below in Figure 3-1. That means that there are different production steps executed inside of it, for example etching the surface in the first chamber, depositing film in the second chamber and heating the wafer to settle the film in the third. This means that there a lot of heating and cooling and many consumables are used to produce a stable manufacturing environment. In other words, a lot of support is needed to ensure each chamber constantly maintains the optimal production environment.

Figure 3-1: Sample multi-chamber semiconductor manufacturing tool [1]

Figure 3-2 shows the inside of such a production tool. There are five different chambers in usage (1-3, C and D), with three different actions (which are not enclosed due to IP restrictions). Additionally, the amount of support systems required to maintain this can be seen, for example, five support pumps and two heat exchangers are used for this tool alone. Eleven different consumables are supplied via the subfab, which is located below the cleanroom and holds most support systems. Additionally, there are the actual chemicals used in the process and the wafer, which is being processed. This in itself shows how complex the supply systems are, however, if taking into account that these then also have different flow rates, pressures, pipe sizes and connectors, a whole new challenge in terms of measurement is opened up.

[1] From:http://www.oxford-instruments.com/products/etching-deposition-growth/tools/tools/system100pro/Pages/system100pro.aspx

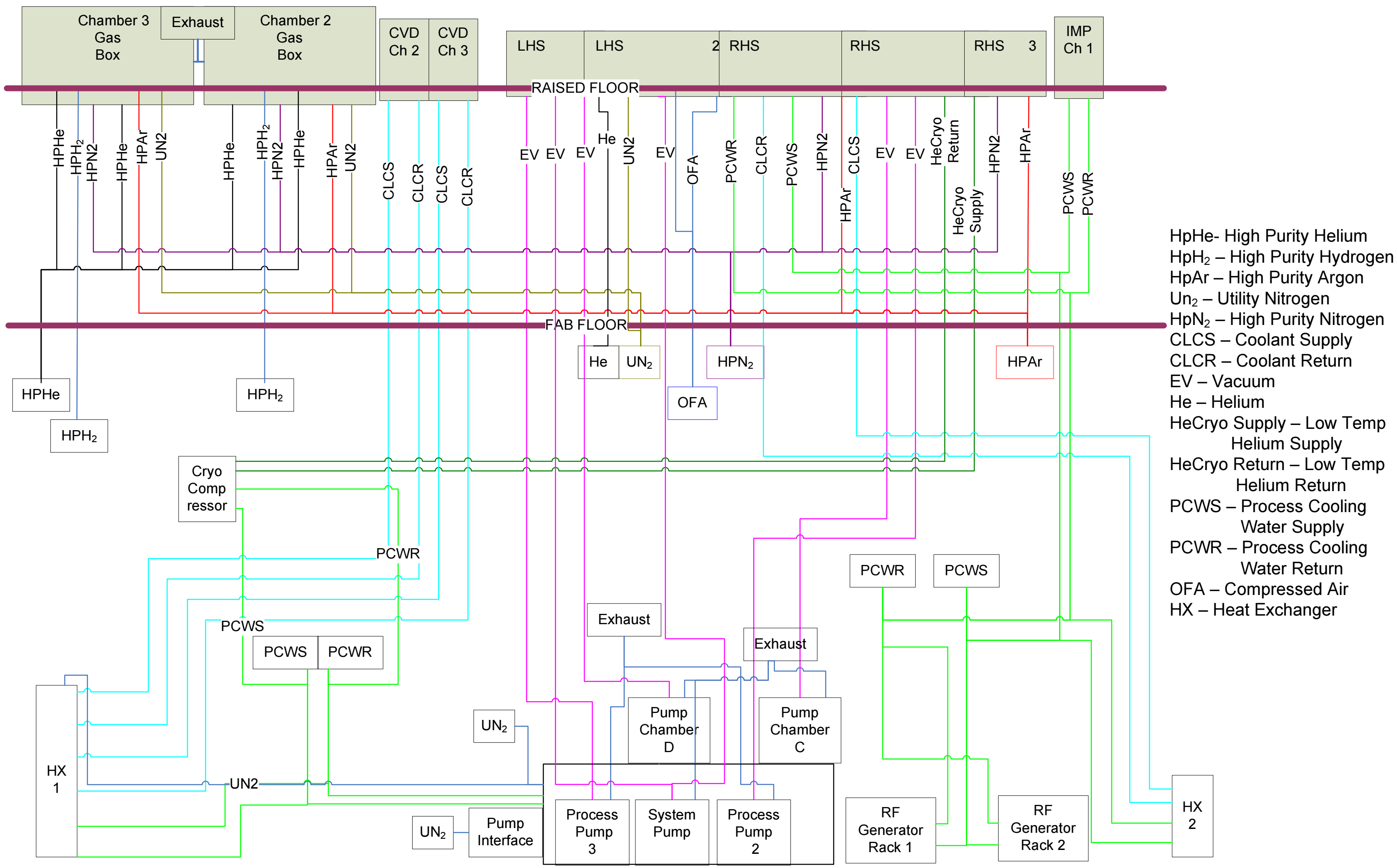


Figure 3-2: Fab and subfab connections of a semiconductor manufacturing production tool [source protected]

Five different gasses are supplied to the tool, which are micro-managed in the gas box supplying the tool. High purity Helium, Hydrogen, Argon and Nitrogen are used directly in the process, whilst normal purity Nitrogen and Helium are used to flush these gas boxes. Additionally, compressed dry air is used in the mainframe of the tool. These gasses are supplied via 21 different gas supply lines, supplying processing as well as production environment gasses, with flow ranging from a few cm^3/h to tens of m^3/h (actual data not disclosed due to IP restrictions).

Two different coolant systems exist, one using PCW (PCWS & PCWR) and one with a different coolant (CLCS & CLCR). These interact at the two heat exchangers (HX1 and HX2), where the PCW chills the coolant, but the PCW is also supplied directly to the tool for different temperature applications. There are two PCW loops supplying seven different parts of the machine, of which, for example, two are concerned with keeping the different processing chambers at two different temperatures. Because of the arrangement of these lines, at least five different measurement points are required to get a full overview of the consumption patterns. Additionally four different connectors are used for these lines with different diameters, again increasing the measurement complexity.

Two more supplies exist, consisting of vacuum and cooled (cryogenic) Helium being supplied to the tool mainframe by subfab pumps. Additionally, exhausts are located on the gas boxes and several process and chamber pumps. Not shown are the over 50 electrical connections that exist in the tool as well as between tool parts and supplying the support systems, nor are PCW and Nitrogen supplied to the subfab systems shown.

When actually investigating the tool in the cleanroom, it was found that very little existing experimentation was present. The only consumables that were tightly controlled were the actual production gasses and chemicals, which also had proper flow meters and digital recording data. Other consumables only had pressure gauges, e.g. UN_2, whilst main PCW lines had visual float type flow gauges. From these visual gauges it was observed that there was very little change in the volume of the PCW supplied independent of tool action.

3.2.2 Application of the TEE tool

There are three factors limiting the usage of the TEE tool. The number of tool supply lines, the difficulty in measuring them (or obtaining accurate measurement from existing instrumentation) and the multi-action chambers. It can be seen that there is a gap between the idea of the TEE tool to characterise tool behaviour and the reality of too many different components in a tool requiring too many different consumables to expect a realistic implementation of the methodology. Therefore, some selection of components and consumables has to take place in order to realistically classify a tool and its actions in environmental terms. This means a much better cost-benefit balance for the factory owner. For multi-chamber complex production tools, it is therefore essential not only to identify which components consumption are important, but also which consumables are worth measuring.

3.3 CO_2 Laser Cutting Tool (Offline)

Because of the limitations of access to tools, employment of external sensors and limited existing tool data, a decision was taken to evaluate a production tool in the engineering workshop of Dublin City University. A Rofin DC015 CO_2 Laser Cutting tool was chosen as there is a wide range of consumables supplied to it (Electricity, PCW, Process gasses) as well as a large control element, and it hence mirrors a semiconductor manufacturing tool. It also offers the unique opportunity to instrument almost all major consumable lines, as well as comparison between models and actual consumption and comparing environmental impacts. The laser is shown in Figure 3-3 below.

Figure 3-3: Rofin Laser Cutting tool and controller

There are four distinct components to the laser system. There is the laser head itself which is centred above a table which moves the specimen under the beam (which is stationary) and is controlled by a controller box which manages all electricity and command supply to the laser. Outside the workshop there is a chiller (not pictured) which supplies chilled water to the system.

Three different types of consumable are used in the laser: Electric power, PCW and purge gasses. Additionally, CO_2 gas is used in the generation of the laser beam and the material that is being worked on, which can be metal, wooden, plastic or glass. The supply circuit of consumables to the tool is shown in Figure 3-4 below.

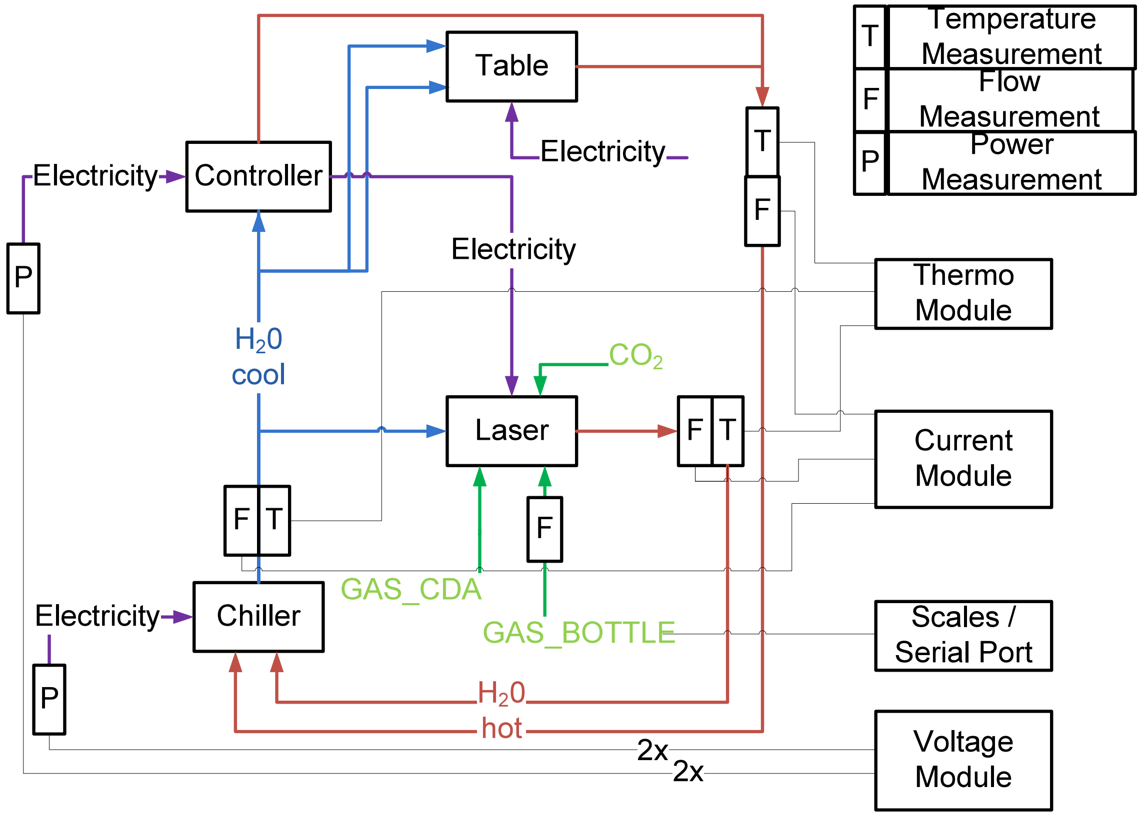


Figure 3-4: Flow of consumables in Rofin DC 015 Laser, their measurement points and the DAQ module

Three separate electrical supplies are used. One for the table, one supplying the chiller and one supplying the controller which in return supplies the laser with power. The table has a single phase supply whilst the other two have three phased power supplies.

The PCW flows from the chiller into the table (with two inputs) and then the controller and the laser, separately from the controller. Whilst three separate gas sources exist, only two are visible and influence able by the operator: Nitrogen or Argon are used as purge gasses and are supplied straight from gas bottles. Compressed air is currently supplied from a compressor which supplies the entire building, but used to be supplied by a standalone compressor which is still located in the workshop. Both supplies have extremely high pressures with small pipe diameters, which are then regulated down to desired pressures within the tool, hence making external measurement difficult.

From Figure 3-4 it is clear that there are some expected relationships between the consumables. One obvious one is between the electricity consumed in the chiller and the flow of PCW to other components. A less obvious one is the indirect interaction of electricity and gas in the laser itself. Indirect in that respect that although no chemical reaction occurs between the two, they are both intrinsically linked to the laser beam generation and protection.

3.3.1 Selection of Monitoring Points and Consumables to Measure

Although a monitoring system that would monitor all consumables at all components would be ideal, it is not physically possible so a selection had to be made. In this case the consumption behaviour of the table was not monitored, as the focus was on the efficiency of the laser system. Additionally, in comparison to the expected consumption rates of the laser and its components, the table consumption was expected to be very small.

3.3.1.1 Chiller Circuit Consumable Measurement

The chiller was located outside the workshop, and maintains a constant temperature within the laser. It has a three-phased electricity supply, of which two phases are monitored with a current transducer (CT) each, as shown in Figure 3-5. The CTs chosen were LEM AP100B10 Models [84], which allow measurements of currents up to 100A and gives out a proportionate DC voltage output of 0-10V.

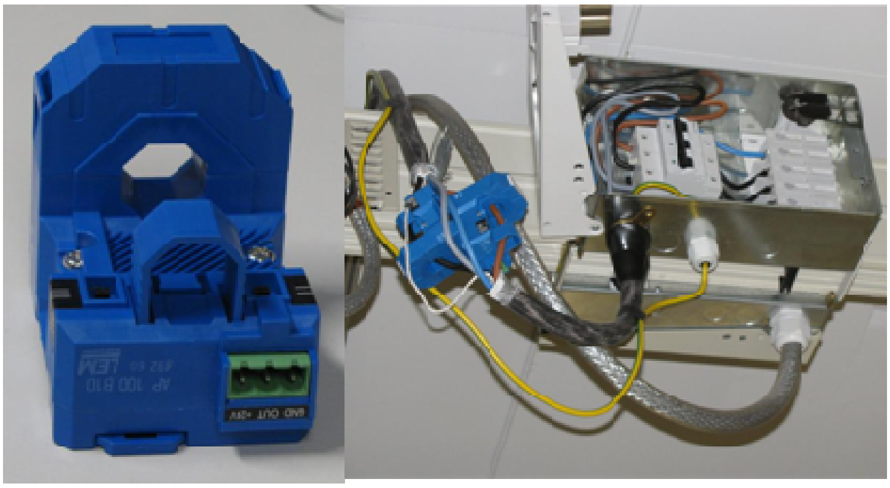


Figure 3-5: Current transducers installed on chiller electricity supply

The actual cooling water flow was monitored with ultrasonic flow meters, which were installed into the lines, thus still breaking the lines but having the advantage of having no moving parts, additionally the cost for three monitors was a lot less than the cost of one non-invasive clamp-on ultrasonic meter. The chosen flow meters were manufactured by Bürkert and of the type 8081 model QN2.5 [85] with a 1 inch external diameter, to fit the existing pipes, as shown in Figure 3-6. They emit a proportional current of 4-20mA for flow rates between 0.16l/min to 82l/min. Additional to the flow meters, shut-off valves were also installed to minimise loss of PCW when they are to be de-installed or fixed. The temperature of the incoming and the two waste stream PCW lines is measured with external K-type thermocouple sensors, as indicated in Figure 3-6, which allows the estimation of the heat removed from the equipment. This three-pronged approach allows to link temperature changes to flow changes and the electricity consumed in this process.

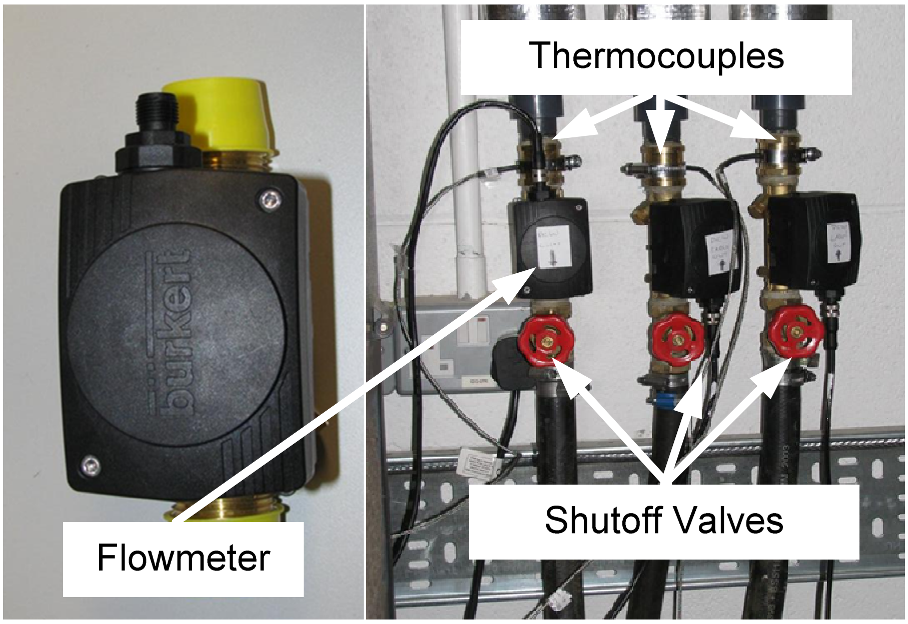


Figure 3-6: Ultrasonic PCW flow meter and temperature sensors installed

3.3.1.2 Control Cabinet and Laser Consumable Measurement

Figure 3-7: Current transducers installed on control cabinet electricity supply

The control cabinet has a three-phased power supply and is again monitored with two current transducers, identical to the ones monitoring the chiller load, and their installation is shown in Figure 3-7. It also supplies electricity to the laser itself, so the consumption is expected to be dominated by the laser state, like idling or processing.

The gas supplies of Compressed Air and Nitrogen/Argon, which are supplied directly to the laser, were to be monitored with mass flow meters. However when they were installed and tested they could not withstand the pressure in the pipes, which is extremely high in the laser supply lines, as they are straight from the gas bottle or compressor. This problem exists for most flow meters with small pipe diameters, and those rated for higher pressures or ultrasonic ones, are generally only for larger diameters, therefore another method for gas measurement has to be found.

In this case, as the Nitrogen/Argon is supplied straight from the bottles, whose volume does not change and supplied in the tool at a constant pressure (thus giving constant weight loss), the weight lost from the bottle over time can indicate the volume of gas used, using the universal gas law. Therefore, digital weighing scales were installed under the in-use gas bottle. No solution of measurement for the Compressed Air was found, so although it was meant to be measured initially using the same flow meter type (calorimetric) as the Nitrogen/Argon, it could not be measured at this time.

An Ohaus Defender 5000 scale was purchased, which has a granularity of 0.01kg and a 1-250kg range and installed, as shown in Figure 3-8. It allows dynamic measurement of the weight, and indicates the weight drop in 0.005kg steps (although the certifiable minimum weight difference is 0.01kg). Additionally, due to having a digital output via serial port, digital recording of this data was possible.

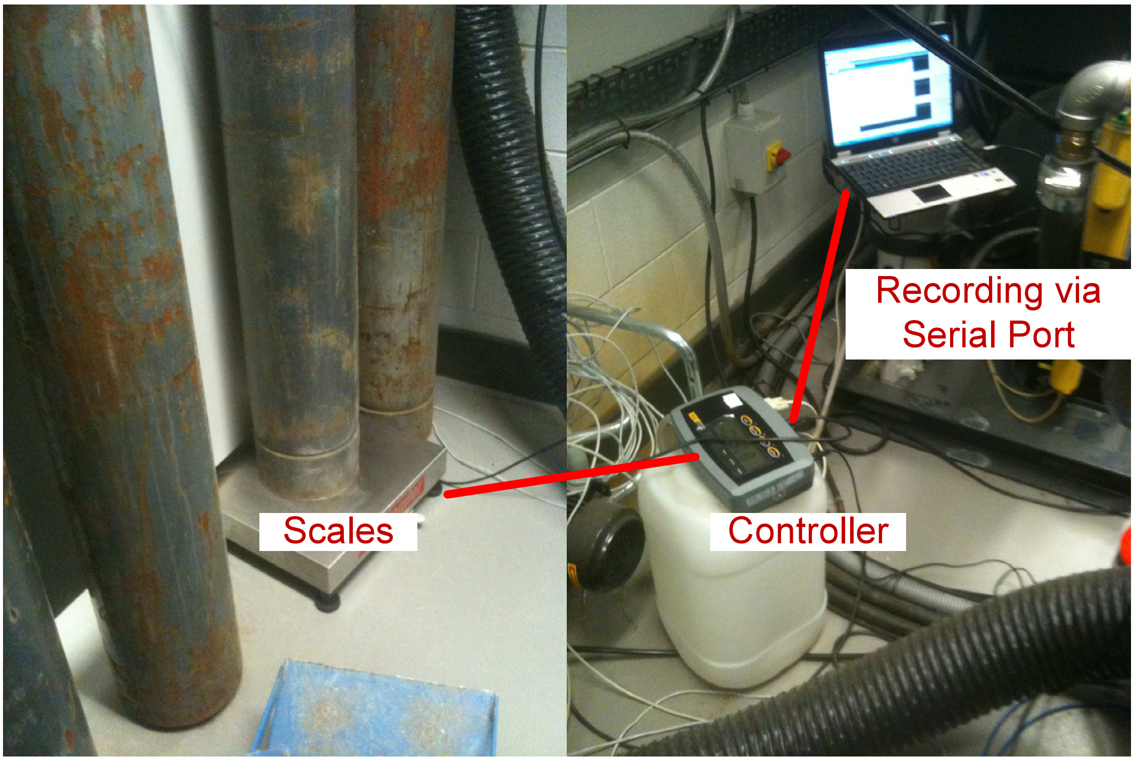


Figure 3-8: Defender 5000 Scales installed

3.3.2 Data Acquisition

The different sensors described above have different analogue outputs: Voltage from the CTs with a 0-10V range, Current with a 4-20mA range from the PCW flow meters and mV for the thermocouple output. Hence a Data Acquisition (DAQ) system was needed that could support and manage all different inputs. The National Instruments m-DAQ system supports various different analogue and digital inputs through the usage of modules and was therefore highly customisable and suited to the multitude of inputs in this project. Four modules were purchased with a view to coping with almost any input encountered and hence future proofing the DAQ system for other measurement purposes. One thermocouple module allowing any thermocouple temperature recording (NI 9211), one voltage input module (NI 9205) supporting the current transducers, one current module (NI 9203) supporting the flow meters and one digital input/output module (NI 9403) for future signals such as tool-signal integration for recording tool actions.

The advantage of this DAQ system over other standalone systems such as the OMEGA O320 series [86] is that the sampling frequency can be very high as well as having virtually inexhaustible data storage capacity due to its connection with the PC.

Table 3-1 shows the different consumables measured, their variable names in the DAQ and the location of measurement.

Table 3-1: Overview of measured consumables and their designated input names

Variable name	Consumable, Instrument	Description	Measurement location	Port in module, module
[PCW_C_IN]	Cooling water Flow meter	Cool PCW IN	at wall	al0 (Current Module)
[PCW_T_OUT]	Cooling water Flow meter	Hot PCW Table OUT	at wall	al1 (Current Module)
[PCW_L_OUT]	Cooling water Flow meter	Hot PCW Laser OUT	at wall	al2 (Current Module)
[PCW_T_C]	Cooling water Thermocouple	Cool PCW IN	at wall	a0 (TC Module)
[PCW_T_T]	Cooling water Thermocouple	Hot PCW Table OUT	at wall	a1 (TC Module)
[PCW_T_L]	Cooling water Thermocouple	Hot PCW Laser OUT	at wall	a2 (TC Module)
[ELEC_CAB_1]	Electricity Current Transducer	One phase of Controller Supply	in cabinet	a0+a8 (Voltage Module)
[ELEC_CAB_2]	Electricity Current Transducer	One phase of Controller Supply	in cabinet	a1+a9 (Voltage Module)
[ELEC_CHILL_1]	Electricity Current Transducer	One phase of Chiller Supply	ceiling	a2+a10 (Voltage Module)
[ELEC_CHILL_2]	Electricity Current Transducer	One phase of Chiller Supply	ceiling	a3 + a11 (Voltage Module)
[GAS_BOTTLE]	Nitrogen/Argon Scales	Bottled Gas Weight	Underneath current bottle	HyperTerminal Connection (RS232)

Data from the scales were read out via the serial port connection provided. Originally, to integrate the scales with the DAQ used for the other instruments, the direct signal from the load cell was meant to be amplified and then wired into the DAQ. However, despite using shielded cable, the noise in the signal was too high to get the granularity required and provided consistently by the serial port (0.01kg). Therefore, the serial port was ultimately used to obtain the results.

3.3.2.1 Signal Recording

The signals obtained from the sensors and converted by the mDax unit were recorded using the Signal Express program by National Instruments. This displays incoming data and records them internally. Once the program has been stopped the files can be exported. The configuration of the signal properties in the program were quite challenging and finding a suitable sampling frequency was difficult. Achieving stability in the program over extended periods of time was problematic due to the sheer amount of data recorded, so this is being counteracted by saving frequently.

3.3.3 Management of Data generated

The sensors were installed and signal wires were all merged into a Box, which contains the DAQ system. This ensures that no dirt can reach the DAQ as well as allowing good cable management and having one easy access point for tests and problems. The content of the box is shown in Figure 3-9 below.

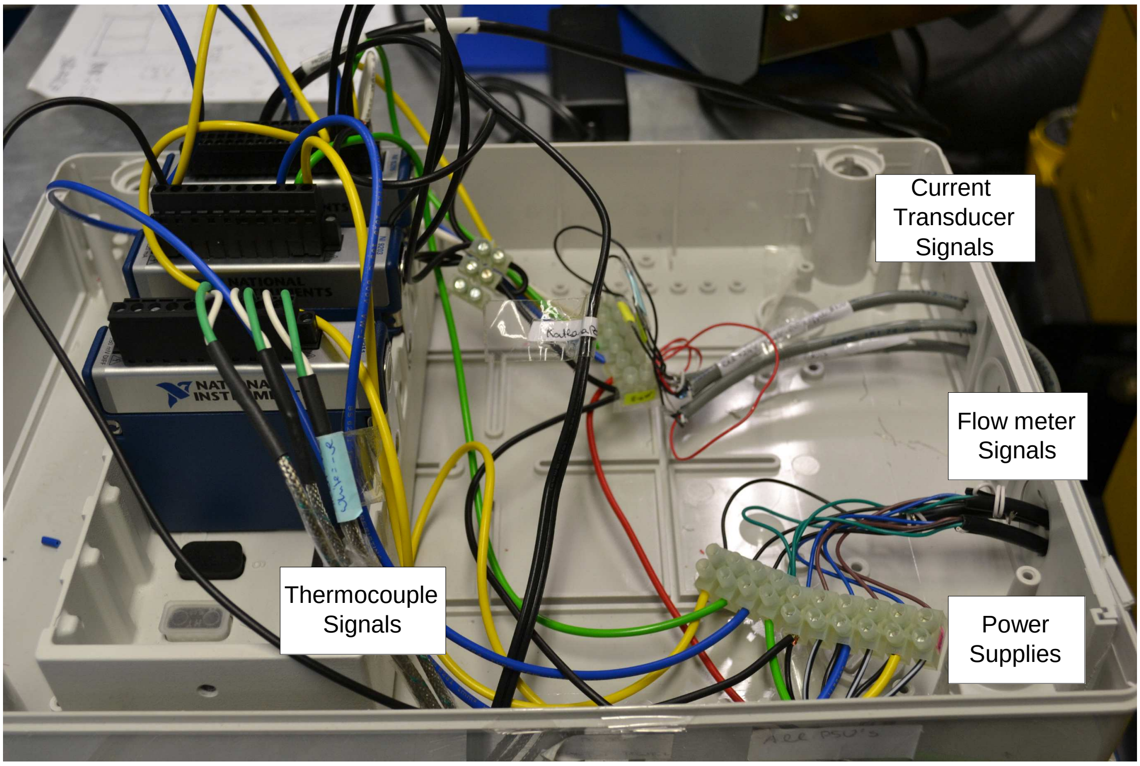


Figure 3-9: Wiring of all sensors to DAQ

Due to the DAQ's connection with the PC the data management is also simplified as the Signal Express program driving the sensor data has exporting facilities for MS Excel and as text file. However due to the vast amount of data generated and the resulting large files, the limit for exporting to MS Excel was exceeded. Exporting to text file was still an option, and even though these can no longer be opened and viewed, they still allow manipulation through Matlab. Therefore text files were used to export and store the original data. For long running measurement periods, several text files were created as frequent saving within the program meant less chance of data loss or program instability.

This stopping and starting was done during idling and took an average two seconds between each. When merging different files of one session, the header supplied by the DAQ with each file has to be deleted. Therefore a textfile splitting program was used to split each individual file into chunks of 5MB, so that it can be opened by MS Notepad, then the header was deleted (only existent in the first of the split files). After deleting the header for each separate original file all split files were merged together into one textfile which was then processed further in the Matlab programs created.

A sample file containing header and data is shown in Figure 3-10. Point 1 shows the date and starting time of the experiment. Point 2 shows the data recorded and the corresponding variable labels, in this case for the PCW flow. Point 3 indicates the time step used (*dt*).

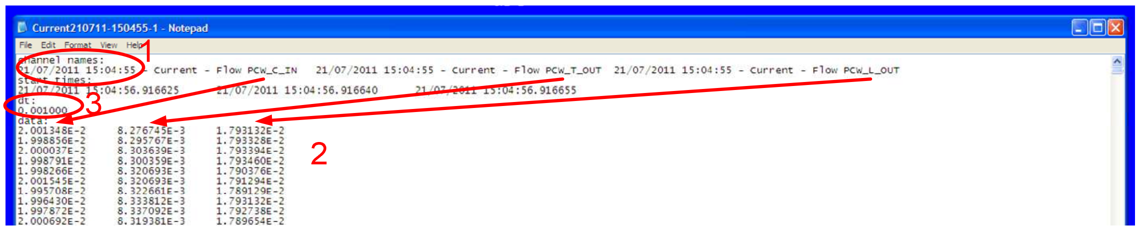


Figure 3-10: Screenshot of a source text file inclusive header

3.4 Display Programs and Data Manipulation

Whilst Matlab offers a great diversity in its programming, it also has limitations, especially when reading in large amounts of data. This is due to how memory for variables is allocated as well as limitations in the virtual memory when using it in Windows XP [87]. This problem was encountered many times in the program development stages.

3.4.1 Preliminary Programs – Current, Flow, Temperature

At the start of the data display programming, the *textread()* function was used to read in the data files (including text splitting and text merging to remove the header as explained above). The aim of these programs was to read in the data from all three modules (the weighing scales had not been deployed at this point) and display the data for PCW flow and temperature, as well as electric current used on a single plot. However, when files of longer measurement periods were read in (in excess of than 30 minutes) the virtual memory could not cope with the amount of data supplied (10 separate channels with 1,800,000 data points per 30 minutes at a sampling rate of 0.001s). Additionally, the processing time for even these small datasets was around 80s. A better approach was found when using the *textscan()* function which allows definition of what is read in from a file and where, and definition of the variable class for storage. The program included processing the data in separate batches and run time was reduced to around 10-15s depending on the file size. This could read in the data from all three channels at once but again the virtual memory limited the plotting function of them. Therefore only single curves could be plotted at once.

From these programs it became clear that within the limitations of the operation system, the granularity had to be reduced to display longer measurement periods on one graph. The comparison of the consumables on one plot is especially important, as one key aspect of the analysis is the relationships between the consumables and the tool actions, and they can only be seen if corresponding time frames are shown in one graph. Therefore, for the final programs, the granularity was reduced to 0.01s, meaning that the memory required was reduced by a factor of ten, giving a better opportunity for long-term recording and plotting.

3.4.2 Final Programs – Current, Flow, Temperature

For each of the datasets (with removed header and merged) within the text file, the data was read in separately for each module, in the 0.001s granularity, using the textscan() function and then the different channels were separated (i.e. separate 3 flows etc). These plus the calculated running time (taken from the amount of data points and expressed in minutes) were then saved into .mat files, which allow saving of Matlab workspaces variables using the *save()* command. This program is shown in Appendix A. However, due to the usage restrictions of the *load()* and *save()* commands, several programs were to be used instead of one, as the loading and saving has to be done manually. But this meant a significant reduction in the file size, from 329MB to 109MB for a 150min recording, as well as easier access within Matlab to the data. Then, another program, utilising the *loop()* function, sampled every 10^{th} value from this dataset, reducing the file size even further, to e.g. 9MB for the previous case and hence reducing the sample size to 0.01s. This is shown in Appendix B.

For future development, these programs could be optimised and merged if the data management can be improved. Under Windows 7, the virtual memory is increased so that potentially the plots could be made with the original resolution for any recording time.

3.4.3 Preliminary Programs – Gas consumption

The data returned from the weighing scales shows the weight of the bottle dropping over time. However, the weight lost from the bottle has to be converted from a mass flow rate to a volumetric flow rate so it can be compared to the PCW. Data samples were taken at an average of 0.0012s intervals (this is dependent on the data communication between the devices). Although it is clearly visible to the human eye where the consumption occurs (i.e. a drop in the weight), finding a programming solution to this problem was more difficult. In determining the rate of change for each point, only marginal changes occur as it is dropping at 0.005kg intervals between adjacent data points. Additionally, these rates of change at each point need to be related back to each other so that the actual times of consumption are shown. In preliminary programs, it was thought that using the gradient would allow for an easy way of determining the usage/idling positions. However, for the final solution the original weight loss data was used. Again, similar to the data obtained from the DAQ modules, the high sampling rate had to be reduced. This time not due to the data management but because between the downward steps (0.005kg), there were large amounts of data points, and thus made processing difficult. Especially since there is a large number of false drops and increases. Every 7th data point was used, reducing the number of points by a factor of 7. At the high sampling rate, there are too many points between the weight drop stages to easily process the data. At the lower sampling rate, between five and nine data points are between downward steps which makes for much easier processing.

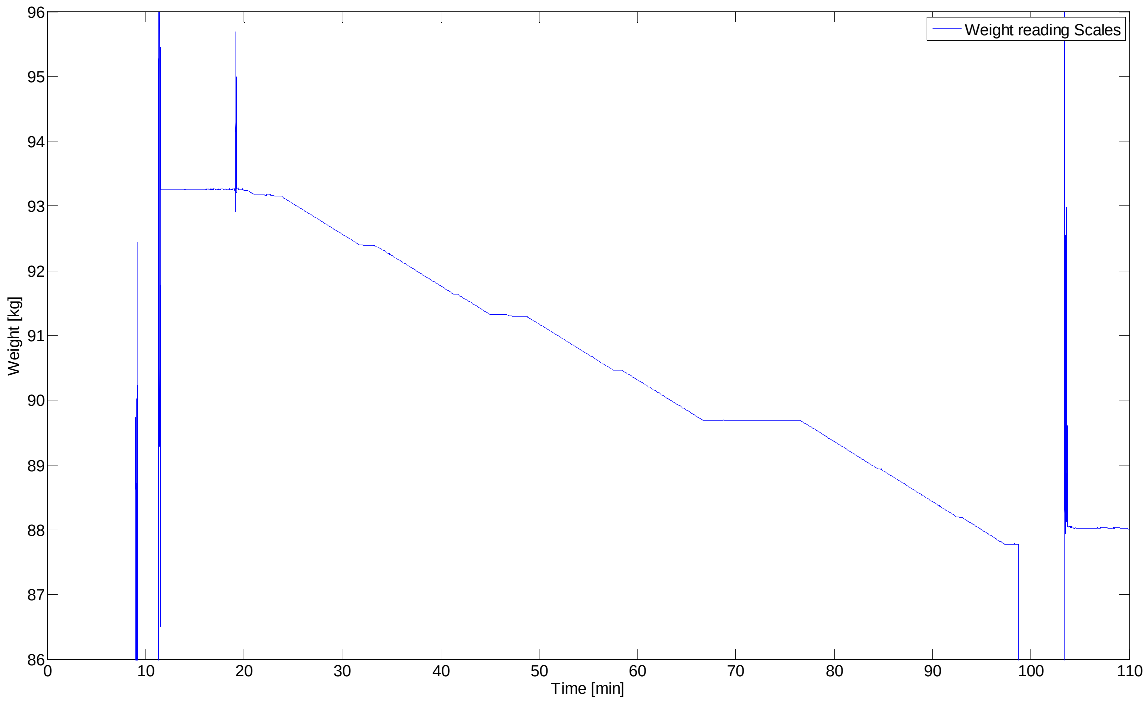


Figure 3-11: Gas Weight Loss Curve (High Sampling Rate)

From the weight loss diagram shown in Figure 3-11, it can be seen that there is a lot of disturbance at the start of the measurements, when the gas bottle is lifted onto the scales, followed by a brief settling period. Similarly, there is a lot of disturbance when the bottle is touched in between measurements or when it is removed. This data hence has to be disregarded in the final assessment. However, it is not possible to avoid this, as the bottle cannot be left on the scales as the proprietary software of the scales cannot start up correctly when a (heavy) weight is left on it.

3.4.4 Final Program – Gas Consumption

The initial programs developed tried to determine start and end points of the slopes and their corresponding weight values. However, due to the weight not constantly dropping and at times increasing due to disturbances in the systems, this method was not successful in determining the actual flow data. Similarly, if the gradient between adjacent points was found, again the disturbances and large amounts of data between drops prohibited a reasonably clear output. As a final solution, a method was developed based on the difference between adjacent points and looking at forthcoming data to determine whether gas flows or not.

The final program calculates the difference between two adjacent data points and if it determines a negative difference, and there is another negative difference present in the next 10 data points, then it determines this point as gas flowing. If there is no difference, but there is a negative difference in the next 10 data points, again it determines gas flowing. This eliminates all positive spikes (as seen in the weight loss only data), but also creates false positives if there is only a small gas loss due to leakage between actual processing steps. Any leak or false drop (i.e. dropping and rising back to the original value within a few data points) is intensified as the ten steps beforehand also determine this point as a flowing gas step.

A secondary filtering is then applied to the data obtained. This again compares two adjacent points, and determines the corners of the consumption spikes. If the second point is larger, it assigns a '1' to a storage variable, or if the second point is smaller, it assigns a '2' to a second storage variable. The indexes of these points in both variables are then found, and the weight and time data at those indexes is used to determine the slope for that particular consumption segment. This is then used, in combination with the universal gas law to determine the volume in litres flowing per minute and stored into a final variable, which was initiated with zeros, so that all non-consumption points are assumed to be zero. Again, some problems exist with this program, mainly due to the loading and unloading of the scales (spikes at start and end of program) and due to the small fluctuations, which are again emphasised by this by having extremely high slopes and therefore extremely high consumption rates. The original weight loss curve and the resultant flow rates obtained by the program are shown in Figure 3-12, and the program is shown in Appendix C.

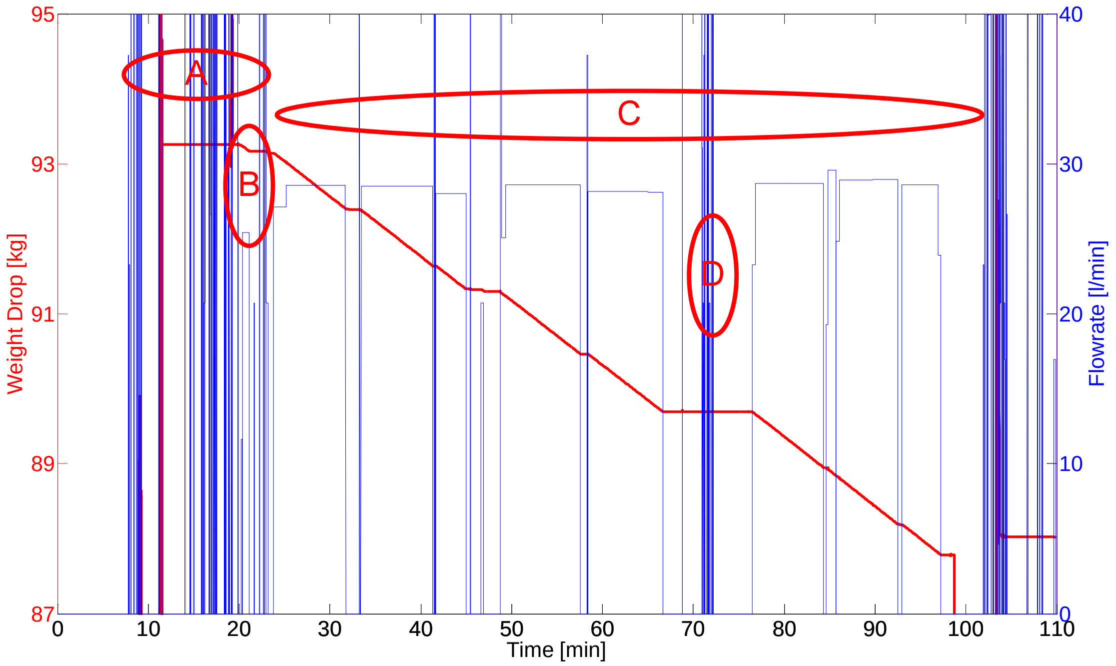


Figure 3-12: Weight Loss vs. Calculated flow rate from sample data

This Figure shows the difficulty in obtaining easily read data from this final automated methodology. A lot of noise is created in part A, due to the weight still settling. This also means small test runs, such as B, are not obvious as actually indicating flow. For longer flow periods, such as experienced in part C, the start and end parts as well as stable flows are actually detected quite well, but still a lot of disturbance exists, such as in part D.

In the final assessment stage, even the results from this were thought not accurate enough, so the start and end weight was recorded manually and, together with the time recorded for tool action, used to calculate the flow rate at each particular segment. This was then coded into the Matlab program, which plots all four consumables against each other, with corrections for different starting and end times, and plotted against the tool action.

Chapter 4 Initial Results and Discussion

4.1 Introduction

Two major areas of investigation exist for the initial results from the data, without involving environmental footprints. One is to determine how each consumable behaves when producing or idling, and how well it corresponds to the tool action recorded manually throughout the experiments. The second is how the consumables and tool behaviour affect each other, for example in terms of increased or decreased consumption volumes.

4.2 Design of Experiments

The laser used in this research has two main functions: Surface treatment or cutting of material. It was intended that both these functions, as well as different material types (metal, glass, plastic, wood), would be tested in a DoE format. The cutting function was set to cut a $4cm^2$ sample repeatedly out of the same material, while introducing different power settings, table speeds, spot sizes and spot overlap values. Similarly, the surface treatment (etching , surface modification) function was to be tested on a standardised $4cm^2$ area. Again power setting, table speeds, spot sizes and spot overlap were to be modulated.

However, due to circumstances beyond the author's control, the conduction of this DoE setup was not possible. Therefore, only experiments/actions conducted by other researchers were observed and recorded. Rather than considering this as an entirely negatively situation, this way of recording actually reflects the reality of taking measurements in an industrial setting. Generally, an observer does not have active say over the tool actions performed in a measurement setup in a working factory.

So for the final data analysis, five datasets were used. Four of these show actual tool processing behaviour with data for PCW, gas and electricity. Table 4-1 shows the Experiments used in the data analysis. More datasets exist that only recorded PCW flow and temperature and electricity.

Experiment A tested the background consumption of the chiller whilst the laser and gas were switched off. Experiment B – D were collected on the same tool operation, which modifies Titanium surface structures [88]. Dataset E tested light scattering on glass for solar power applications [89].

Table 4-1: Experiments Conducted

Experiment Name	Date Logged	Action	Spot Size and % Overlap	Table Speed [mm/s]	Max. Power recorded [W]	Argon Pressure [bar]
A	250511	Background Power consumed (no Gas)	-	-	-	-
B	160611	Titanium Surface Treatment	0.09, 30%	41.7 62.5	100 130 170	2
C	140711	Titanium Surface Treatment	0.09, 30%	41.7 62.5 83.3	100 130 170	2
D	210711	Titanium Surface Treatment	0.09, 30%	62.5 83.3	100 130 170	2
E	250711	Glass Surface Etching	0.09	1.6 8.3	0	1

Experiments B-D were conducted on flat surfaced, rectangular Titanium bars, which were mounted on a larger steel back plate. This is used so that the laser can overshoot the sample when running, so that the power at the laser when modifying the Titanium was always constant at the peak power determined by the operator. This was done because the laser output slightly increases and decreases when the table changes direction, and consistent power is required when modifying the surface. The change in power was also confirmed on the display of the controller which shows the actual power at any time.

4.3 Electricity

Although only the current is measured, with a few assumptions, the apparent and true power can be found, especially if the voltage rating is known. In a WYE constellation, and using the line voltage of 400V given on the rating plate of the laser, the apparent power can be calculated as

$$Apparent\ Power\ [VA] = V_{LINE} * I_{LINE} * \sqrt{3} \tag{3.1}$$

Where V_{LINE} is the rated voltage, and I_{LINE} is the measured current, as in a Wye constellation three phase power system the line current is the same as the phase current. This assumes that the system is balanced. Therefore, for an average 9A phase current drawn in the chiller, the apparent power calculates as:

$$Apparent\ Power = 400 * 9 * 1.73 = 6228\ [VA] \tag{3.2}$$

If a power factor of one is assumed, and this is an educated guess as data does not exist, but for a sensitive system like the laser a power factor correction is expected, the true power is equal to the apparent power.

4.3.1 Electricity – Laser and Control Cabinet

The combined controller and laser consumption corresponds well to the tool action, as shown in Figure 4-1 to Figure 4-3. The plots show the tool action recorded ('Action') in red, and the corresponding power measured in the two CTs on the two controller phases ('Laser 1', 'Laser 2') as blue and black respectively. The two 'Laser' plots should be at the same height with very little variance between them. However, the present gap suggests an imbalance in the system, interfering signals on the signal line or incorrect installation.

During idling, around 3A/2kW are drawn which can be largely attributed to the maintenance of the laser environment. A significant difference exists between idling and production, where roughly an additional 3A/2kW are used. The actual current drawn depends directly on the average power requested by the operator.

Experiment D, shown in Figure 4-1, shows several repetitions of 3 actions at the same power settings, indicated by points 1 – 3, which have table speeds of 83.3mm/s for point 1 and 2 and 62.5mm/s for point 3. It also shows that the power drawn is consistent for each power setting and table speed.

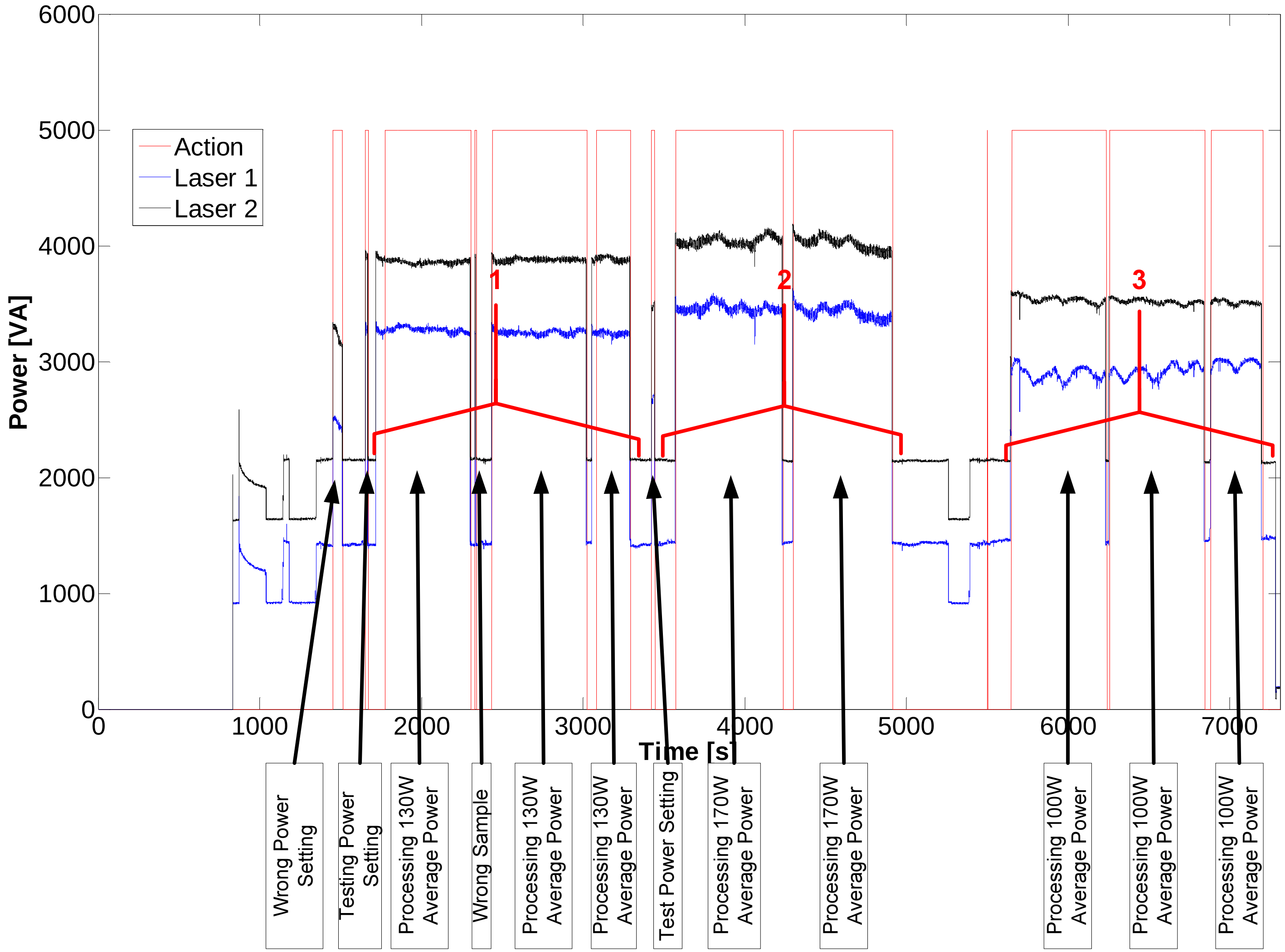


Figure 4-1: Electricity consumption of Laser and Controller, Experiment D

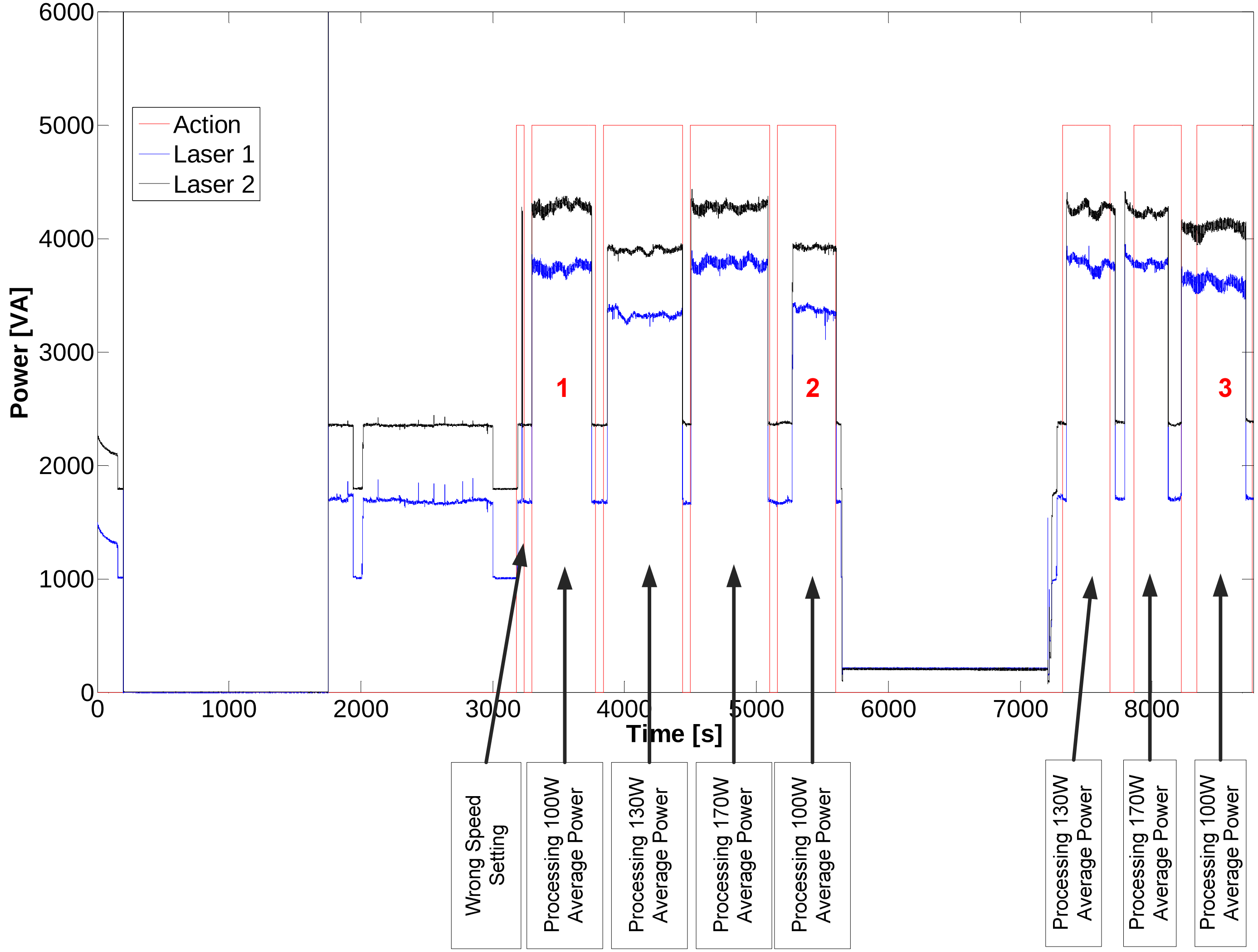


Figure 4-2: Electricity consumption of Laser and Controller, Experiment C

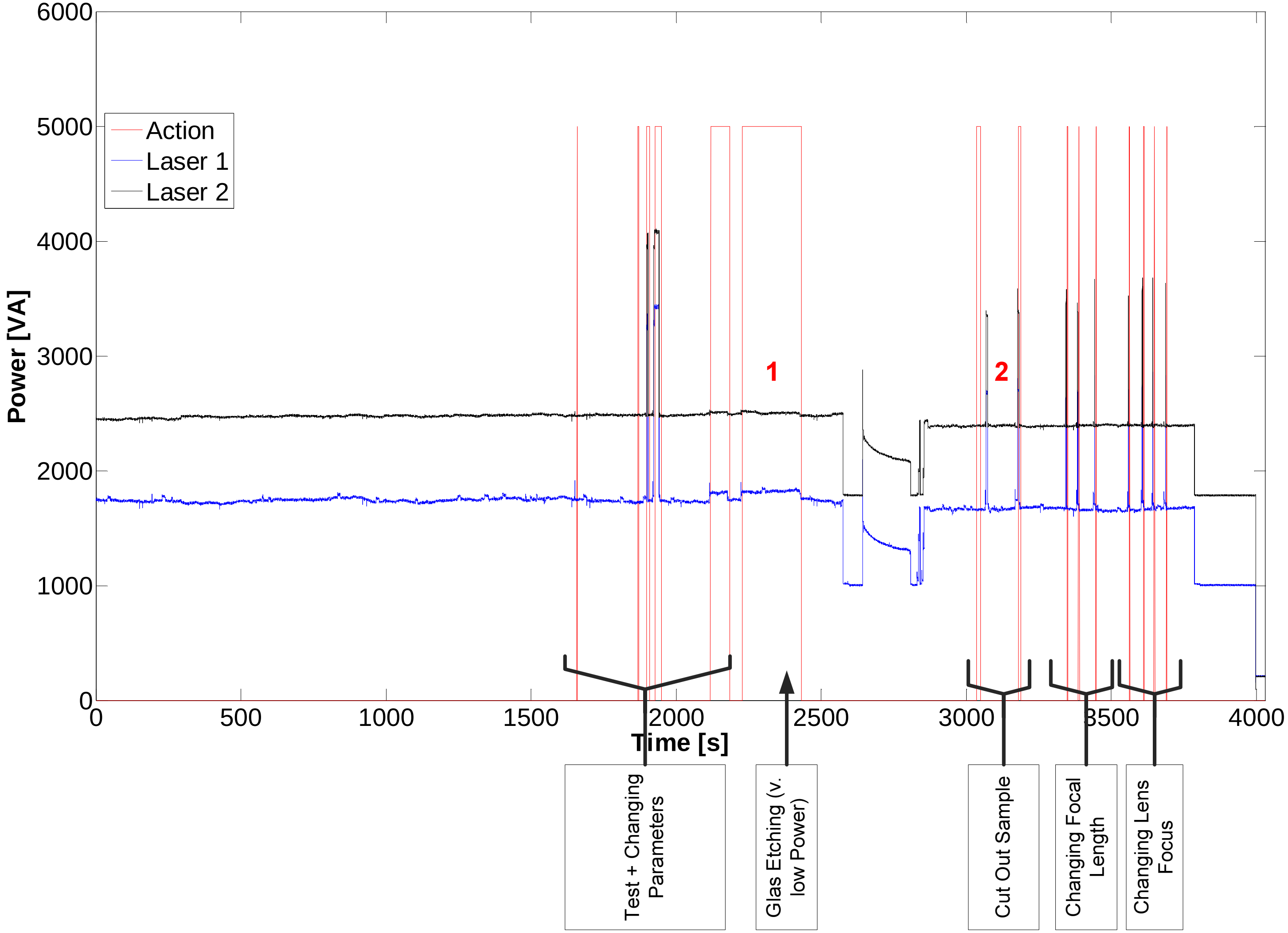


Figure 4-3: Electricity consumption of Laser and Controller , Experiment E

Experiment C, shown in Figure 4-2, used seven different actions with varying table speeds (at 41.7mm/s, 62.5mm/s and 83.3mm/s) and three different power settings of 100, 130 and 170W. It clearly shows a correlation between table speed and power drawn, as shown at points 1 – 3, which have the same power setting (100W), but use different table speeds, with the first at 83.3mm/s, the second at 41.7mm/s and the third at 62.5mm/s. This shows that the speed of the table proportionally influences the actual power drawn by the laser.

Experiment E, shown in Figure 4-3, shows one etching action, at point 1, as well as two cutting actions, at point 2, with several laser parameter changes before and after them. For the etching, very low power was used, but still a correspondence can be seen between the etching action and the actual power measured in the CTs, especially in the blue plot.

4.3.2 Electricity – Chiller

This consumption is most surprising. It was thought, that there would be a more significant change with changing tool states. However, the current drawn stays almost at the same level, at around 8.5A averaged. When looking at the pattern in combination with the tool action, small changes due to the extra heat load when processing can be seen, mainly in the ratio between higher and lower part of its cooling cycle. When the limit temperature is reached (high spike) it is followed by increased consumption due to the cooling (higher part). Once the lower temperature is again established, a lower current is drawn (lower part).

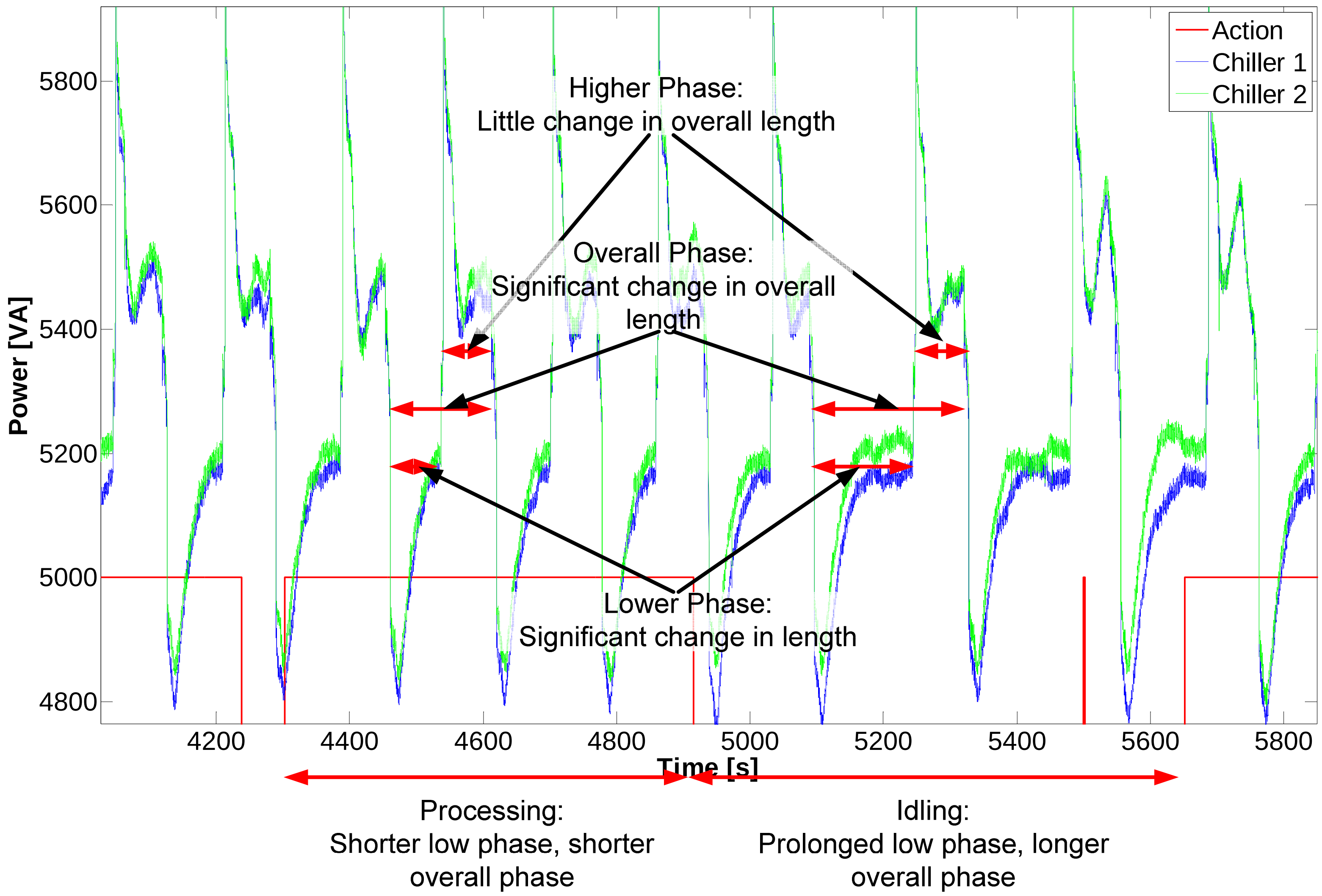


Figure 4-4: Detailed Chiller consumption during production and idling (Experiment D)

Figure 4-4 shows a detail of the chiller consumption over production and idling phases. It is clear that there is a shortened cycle when the tool is cutting. For example four phases occur in a shorter time frame (processing arrow) than three phases during idling, and the length of the lower phase is the determining factor in this, as it almost doubles between processing and idling. During prolonged usage, there is very little ‘resting’ and cooling is mostly involved (higher level) due to the increasing amount of heat to be removed. This coincides with the PCW temperature plot, where a larger gap opens up between inlet and outlet temperature, when the laser is used over a prolonged period of time.

When comparing the power consumption of cutting and idling measurements, several observations can be made. In Figure 4-5, where only the background energy consumption is measured and the laser is switched off, the phases of the chiller are much longer, with seven phases counted over 1500s. The average power drawn in this case is 5.7kWh. When the laser is switched on, and the tool is idling, such as shown at the start of Figure 4-7 and Figure 4-9, the same amount of average power is drawn, but the amount of cycles is much higher at 9 cycles in experiment E. When a lot of processing occurs, as it is the case in Experiment B, shown in Figure 4-6, 10 phases are measured over the same time period.

Additionally, the effect of the outside temperature can also be seen, where the average load of the chiller decreases, from 5.7kWh for most cases (Experiments A, C – E) to 5.2kWh for Experiment D.

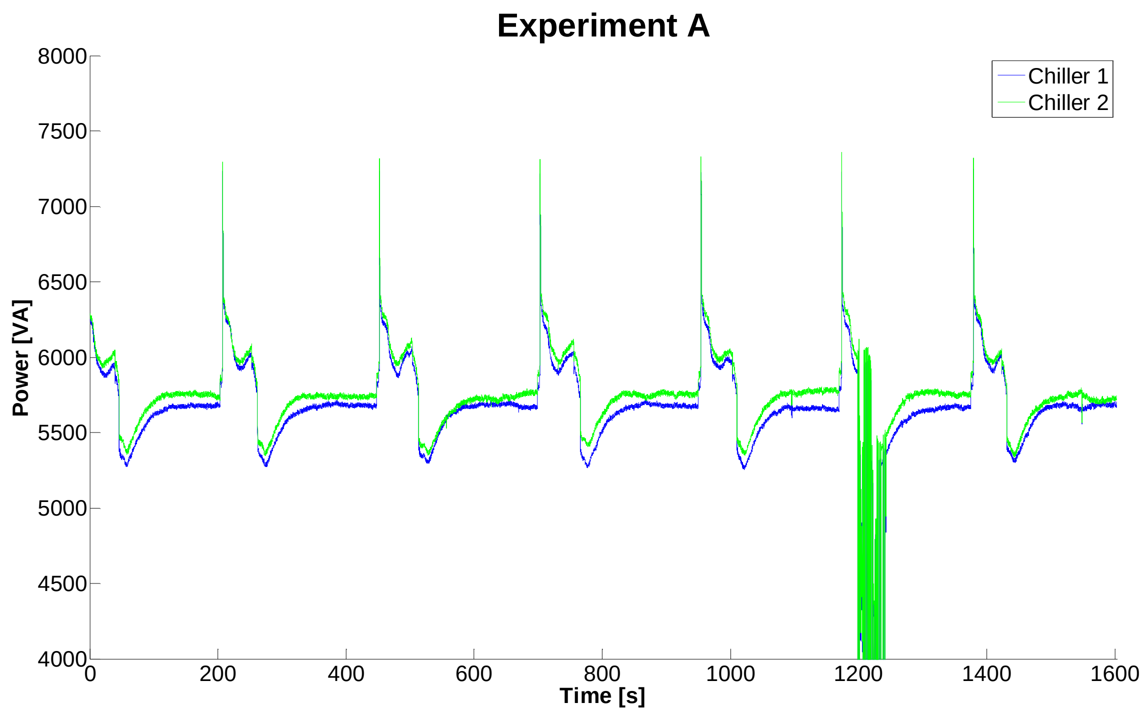


Figure 4-5: Chiller electrical consumption for Experiment A

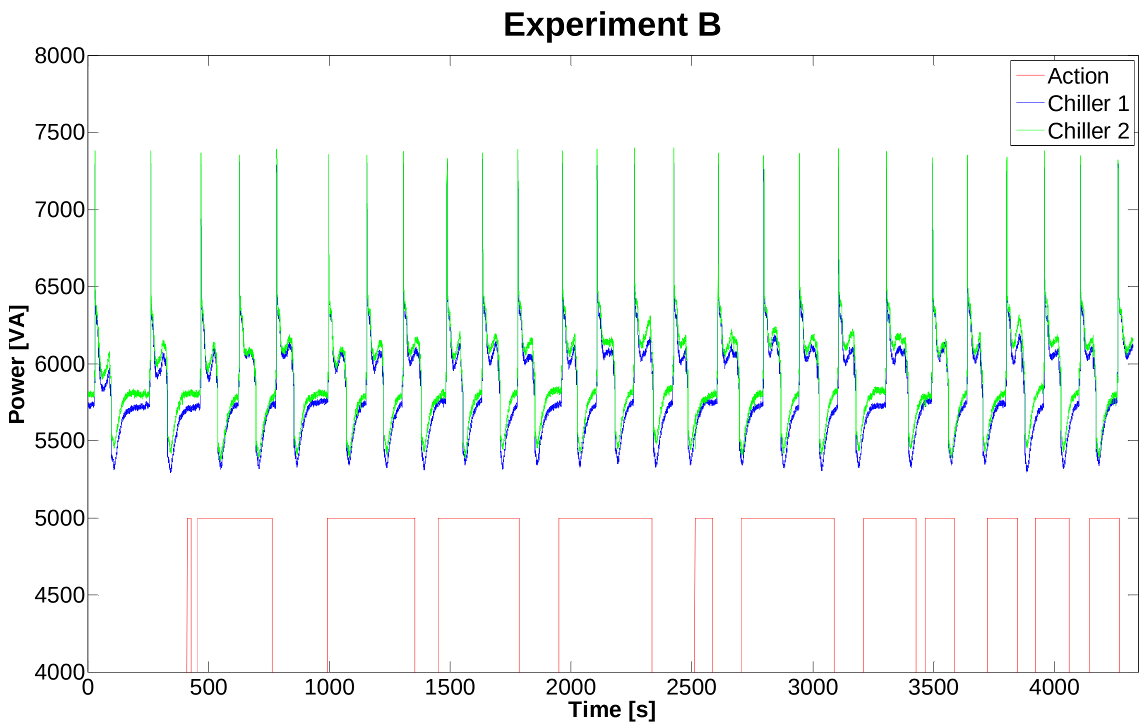


Figure 4-6: Chiller electrical consumption for Experiment B

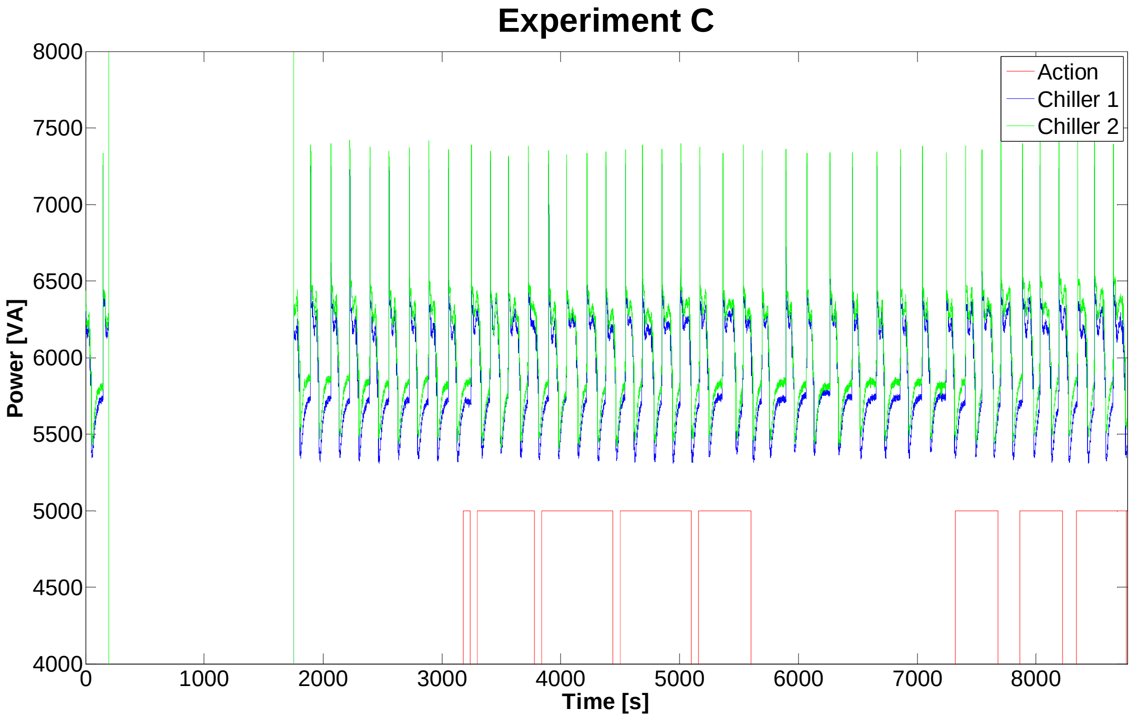


Figure 4-7: Chiller electrical consumption for Experiment C

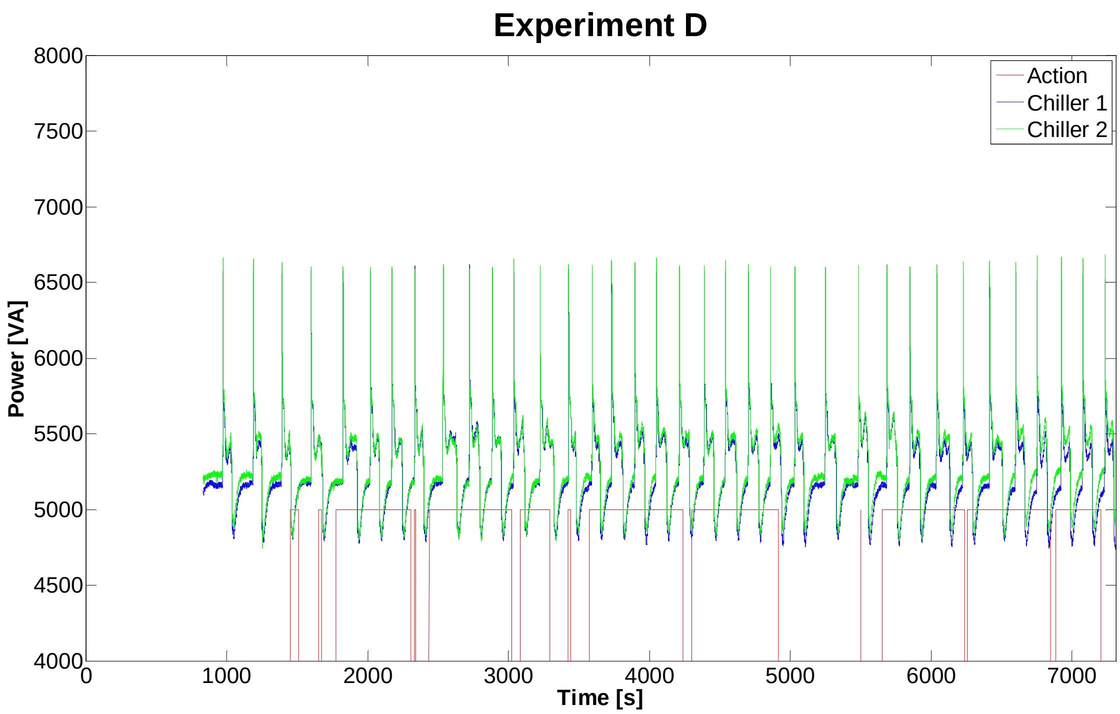


Figure 4-8: Chiller electrical consumption for Experiment D

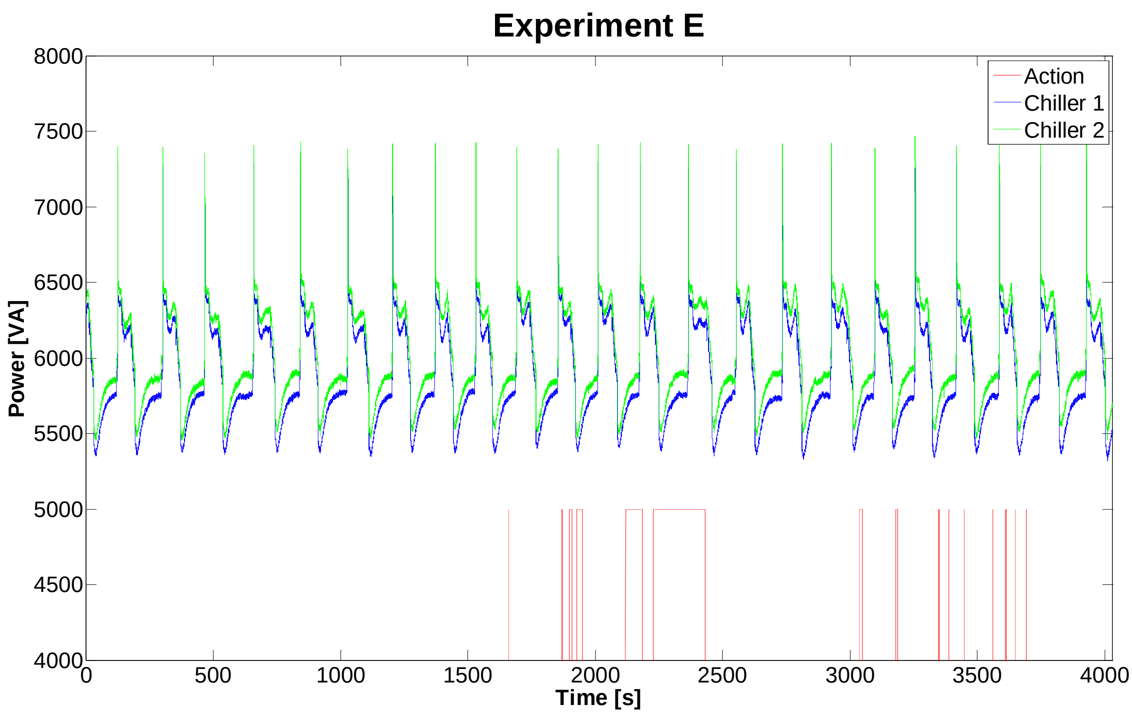


Figure 4-9: Chiller electrical consumption for Experiment E

4.3.3 Process Cooling Water

The PCW consumption volume mirrors the relatively constant pumping action found from the chiller. As shown in Figure 4-10, no change in flow volume exists, regardless of tool actions. It can be seen that the measured value ('PCW In (measured)') is at 82l/min. This shows that the incoming flow is larger than the maximum flow possible in the flow meter. However, as the chilling circuit is a closed loop, the two outgoing flows (PCW Out Laser and Table) will provide the true incoming flow if added together (PCW In calculated). This shows that the actual incoming flow is 93 l/min with the laser flow contributing 71 l/min and the table contributing 22 l/min. These observations are true for all the experiments conducted.

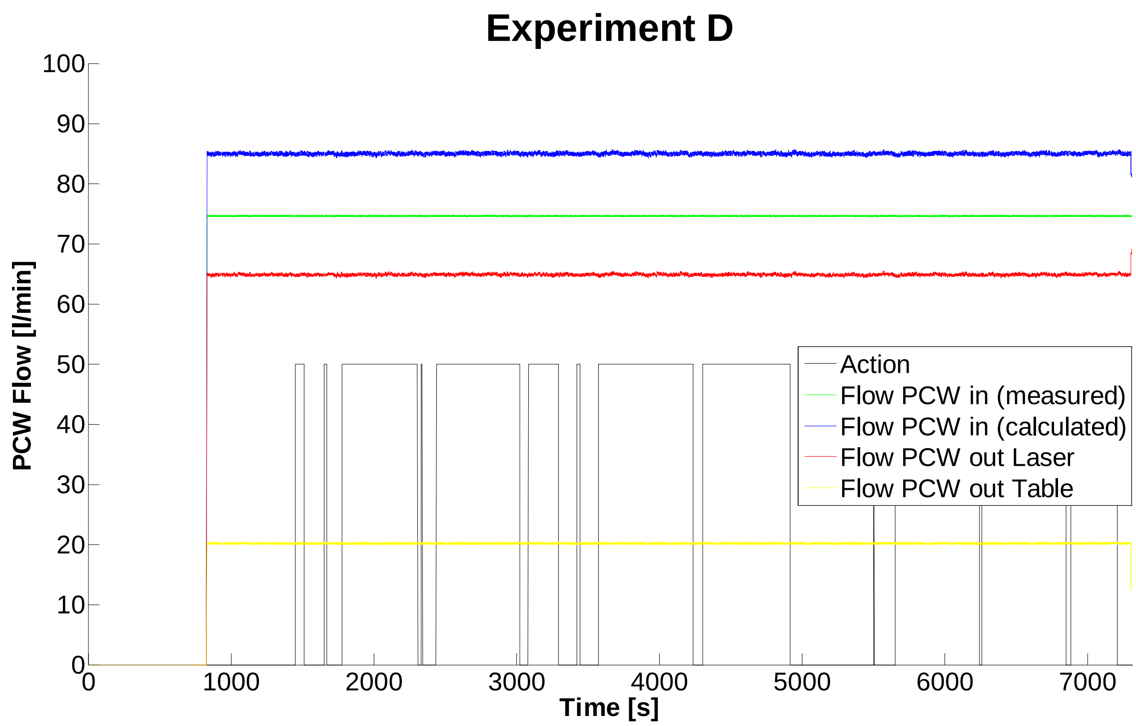
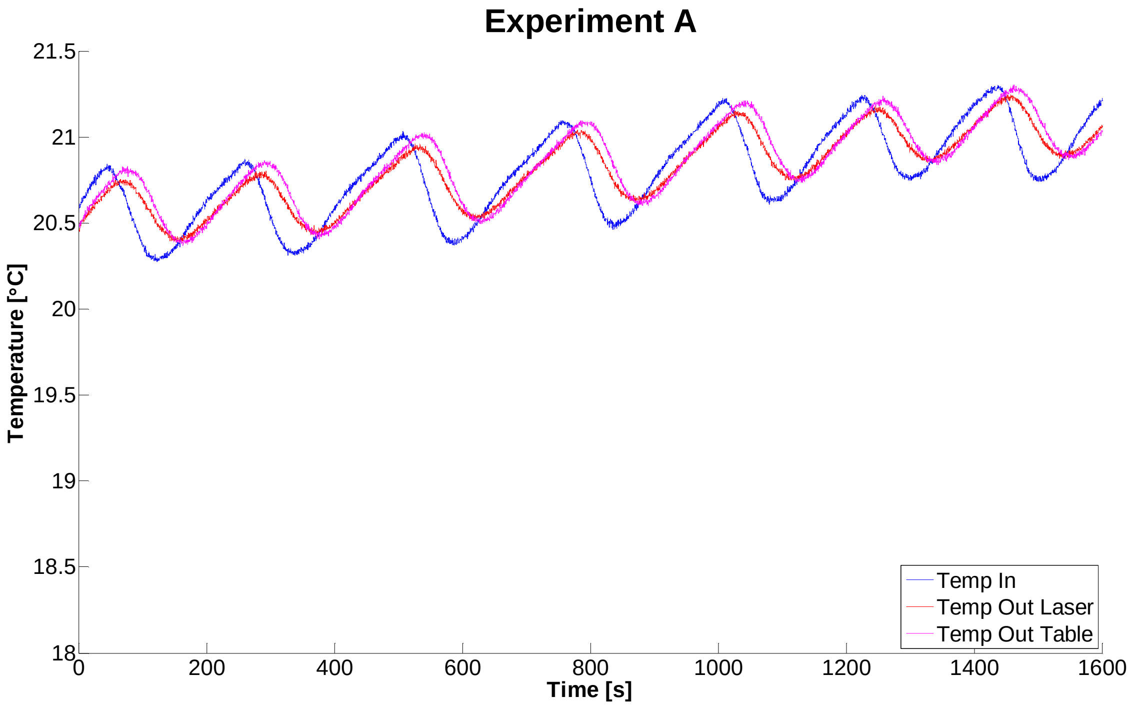


Figure 4-10: Typical PCW consumption

The other specification for the PCW is that incoming and outgoing temperature be no more than 1°C apart. This is because the PCW is used to keep the laser at a constant temperature rather than having to drastically reduce the temperature of the laser. Figure 4-11 shows two temperature curves. Experiment A shows the average temperature when the laser is not on. Experiment D shows the typical behaviour of the PCW temperatures when the laser is alternating between processing and idling.

From Experiment A it can be seen that the average temperature is at 20.5°C when only the chiller is on. Experiment D shows that the starting temperature that day was 19.2°C and averages at about 19.7°C for the incoming temperature. The incoming temperature is generally stable, whilst the outlet temperatures are dependent on the tool action. The outlet temperatures follow the tool actions, as there is a slight increase in the heat load created during processing.



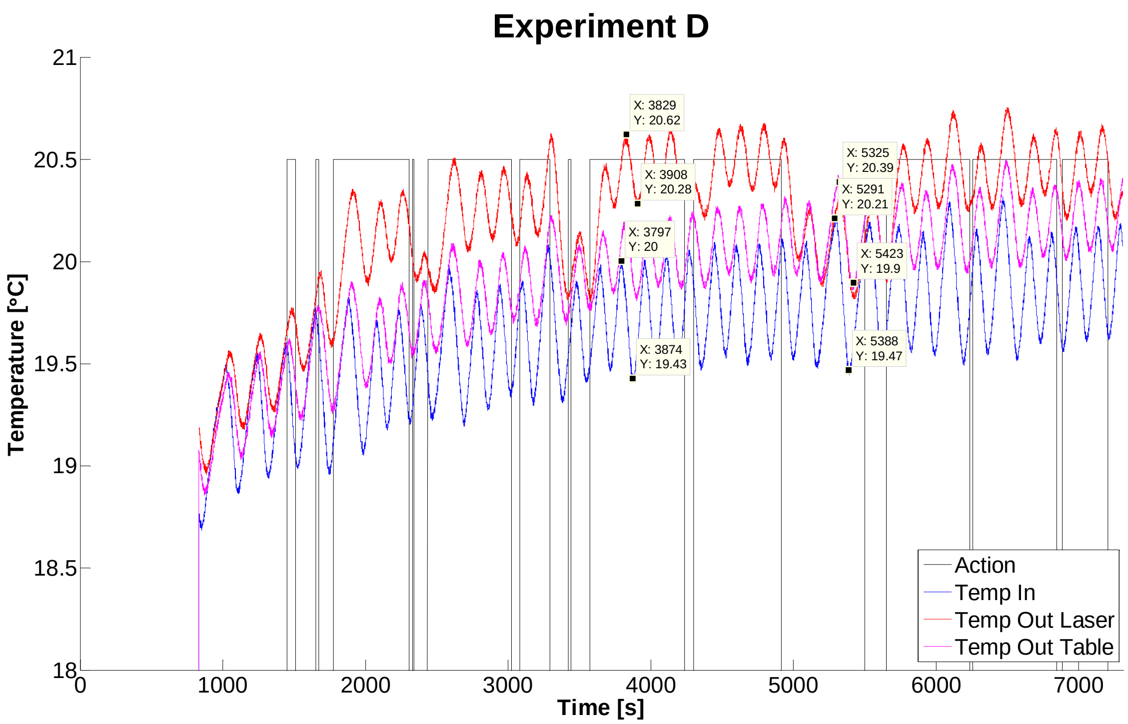


Figure 4-11: Temperature plots – without load (Exp. A) and with load (Exp. D)

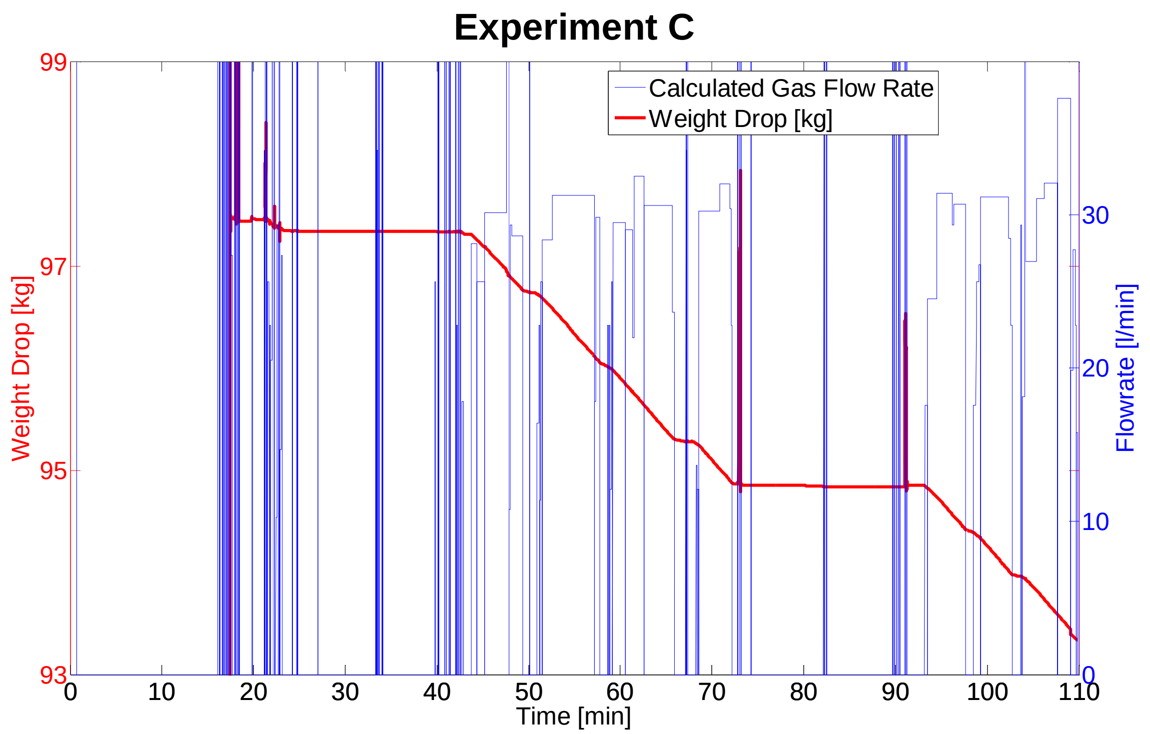
In both experiments there is a slight lag between the oscillations of the inlet and outlet temperatures, which can be attributed to the loop the PCW takes in the laser, which is around 0.35s. Additionally, there is a larger gap between the inlet and outlet plots for processing than for idling. In general, the peaks are much closer together than the troughs. When processing, the difference is between 0.63°C and 0.85°C at the chosen point, and when idling, the gap varies between 0.15°C and 0.43°C on the points chosen, dependent on whether the peaks or the troughs are chosen as a reference.

This change in the temperature behaviour means that although the PCW flow volume does not indicate the tool actions, the temperature of it does. This means that in closed loop systems, temperature gauges and one flow meter on the total flow volume are sufficient to determine the tool behaviour. This of course allows much more cost efficient measurement than requiring flow meters for all pipes.

4.3.4 Argon and Nitrogen

The Gas flow again mirrors the actions of the laser. This is because it shields the laser with gas. However, its calculation was more difficult than anticipated. While the PCW and Electrical measurement were all synchronised and at a dependable time intervals (0.001s or 0.01s shortened), the weight data was transmitted continuously so the time interval changes with every measurement series. Although the option exists to export every second, it was thought that more detailed data was required at the time.

For datasets B-E, the overall measurement time was recorded on a timer, as well as key actions and times written down manually. This is important as some of these usage phases would be disregarded as background noise in the weight data if not for the event log. Additionally, this allows cross linking to the tool activity.



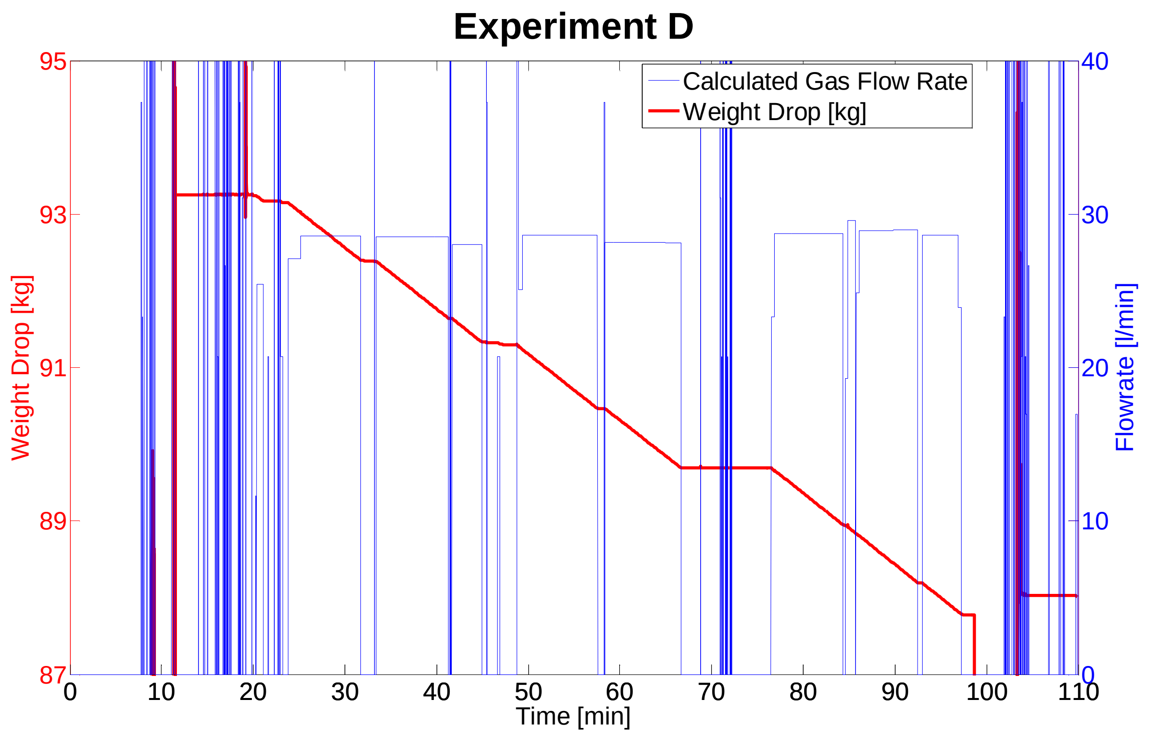


Figure 4-12: Matlab flow calculated vs. Gas bottle weight loss, Experiment C and D

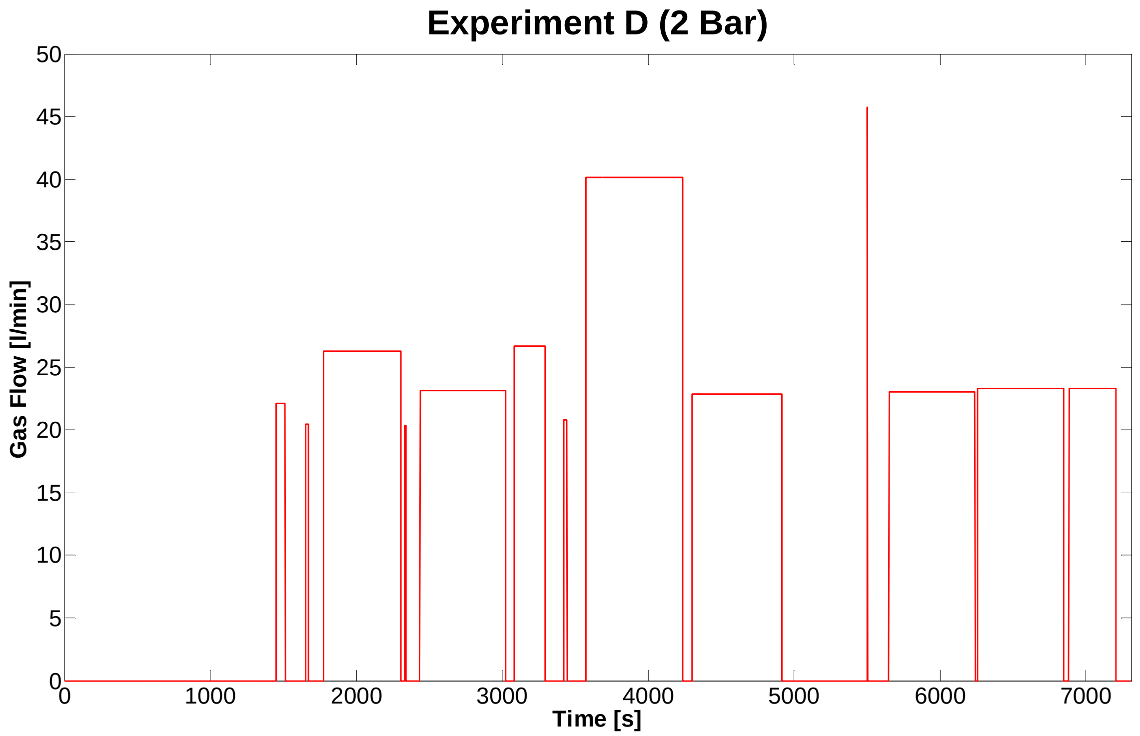
The program developed for converting the weight drop to equivalent flows is not very robust to show all these changes. Whilst working well on one dataset (Experiment D), shown in Figure 4-12, it performs badly on others (Experiment C). However, to get comparable results, clear start and end points are required. Therefore the start and end point as well as data point numbers were collected from the weight drop data and the flows calculated manually in an Excel Sheet, using the start and end times obtained from the electricity data. See Appendix D for full calculation data.

For all datasets, an average of 24 l/min when processing was obtained, regardless of the different pressures used, at 2 Bar (B – D) vs. 1Bar (E). The flows for experiment D and E are shown in Figure 4-13, indicating that although the pressure used changes, the flow rate varies very little, as shown in Table 4-2, which shows the averages obtained for each experiment. One thing to note is that if the laser is used in short bursts, higher flow rates are normally found, between 30 and 45 l/min as shown in Figure 4-13. This might be due to the inaccuracy of time measurement or due to the flushing and refilling of the chamber, which would normally average out over time. Additionally, only flows over 10s can be reasonably determined directly from the weight data.

Table 4-2: Volumetric Gas flow rates for purge gas

Experiment	Average Flow rate [l/min]	Max Flow rate [l/min]	Min Flow rate [l/min]
B	21.4	39.61	7.49
C	21.96	30.81	19.28
D	26.06	45.75	20.33
E	28.12	36.60	22.52
Average Flow:	24.38		

When comparing this average with the one obtained for experiment D using the Matlab program, a discrepancy of 7 l/min is found. This could be due to rounding errors as well as using different starting and ending points, as the program adds 10 data points at the start of each cycle.



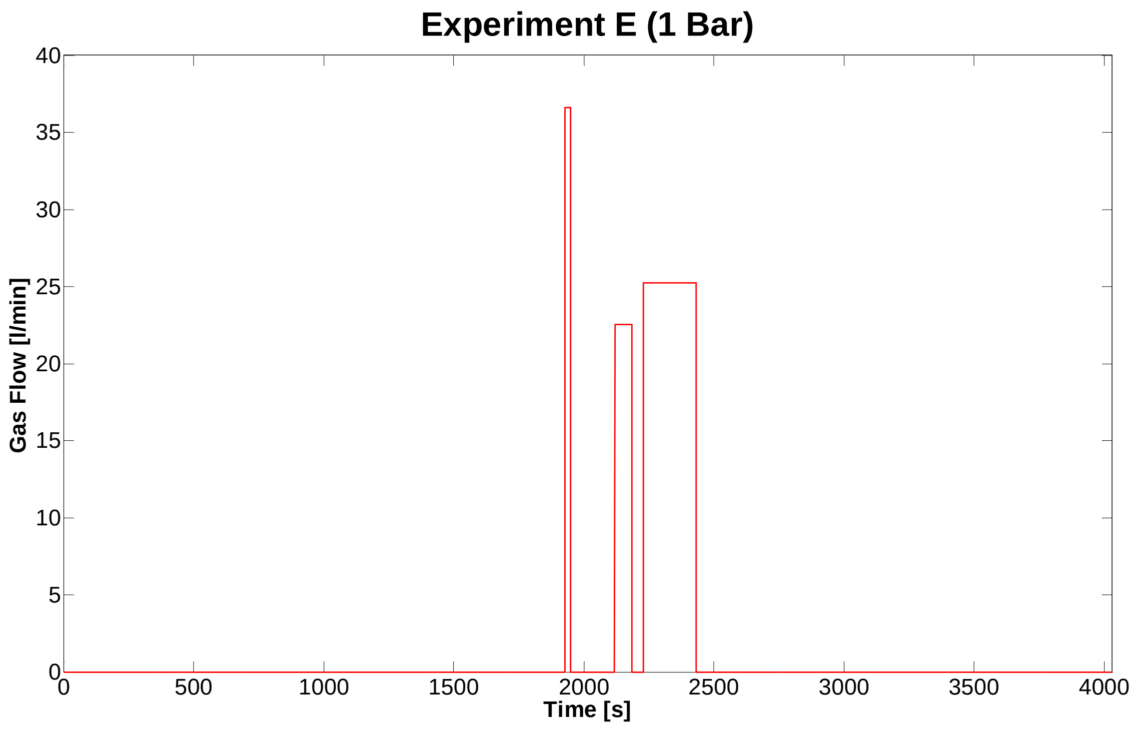


Figure 4-13: Calculated flow rates for Experiment D and E

Figure 4-13 shows two gas flow plots using the manually calculated data. When comparing this to the plot in Figure 4-12 it is quite clear that a lot more tool action detail is shown / recorded and a lot less disturbance is present in the data. However, whilst this is used for this sample tool, a better Matlab program could erase the need for manual recording altogether.

4.3.5 Required versus Measured Consumptions

Table 4-3 shows the specifications obtained from the laser documentation. As these are min/max requirements for safe laser operation, the measured values will have to adhere to them, and any optimisation will have to occur within these boundaries too.

Table 4-3: Requirement detailed by the Laser from manual

Tool Part	Consumable	Details
Laser Head	PCW	>60 l/min, <6bar, 20-22 °C
	Purge Gas (Nitrogen/Argon)	>4 l/min, 3.8-5.3 bar
	Compressed Dry Air	<0.15 l/h
	Electricity	<45 A max current consumption
Control Cabinet	PCW	>10 l/min, <6 bar, 20-22 °C

As seen, the flow rates for the PCW intake of >60 l/min and >10 l/min for laser head and controller respectively are just about met at 71 l/min average, and the temperature range of 20-22 °C is also mostly observed, unless there is prolonged high power processing involved, which means a max of 22.5 °C is reached (Experiments B & C). The electrical current consumption of the laser and control cabinet is well with the stated current consumption, at ~6 A max value for the laser head. For the purge gas flow of Nitrogen/Argon, although obtaining a much higher flow value than specified at an average 24l/min flow, the pressure requested was not met, which is at 1 or 2 Bar due to the operator specifications.

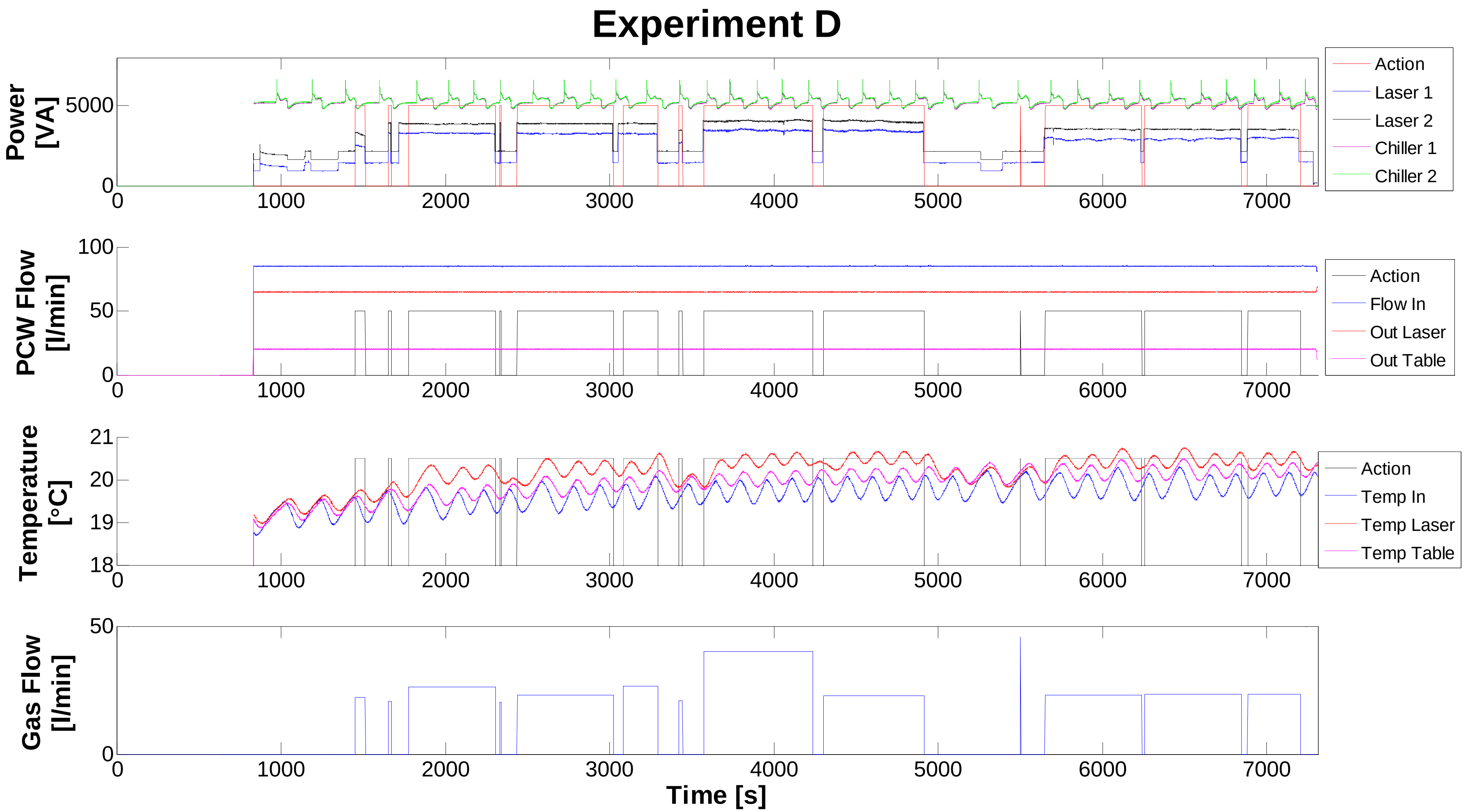
4.4 Combined Curves / Tool Interaction

The four measurement curves and the tool action conducted were plotted against each other to give a better overview of the data at hand. This was also done in a Matlab program, shown in Appendix E.

From Figure 4-14 it can be seen that the electric power consumption of laser and controller and the gas consumption are directly linked to the tool action. Within this, the gas consumptions are constant whereas the power varies with the maximum power programmed into the laser by the operator. The PCW flow volume is not directly affected by status changes, but its temperature reflects the operation of the tool, which in return affect the chiller electrical consumption. From this it becomes clear that the chiller power consumption is dependent on the laser consumption, whereas the gas is independent of this, being only dependent on the pressure chosen by the operator.

The purge gas displays the ideal consumable behaviour – flowing only when needed and otherwise being zero at idling and ramping up and down unless some leakage occurred when the pipe was not connected properly into the bottle. This has not been taken into account in the calculation of the flow rates as it was a human error not a machine error.

The electricity consumption of laser and controller on the other hand is less ideal. Even though a difference between processing and idling exists, ranging from 2.1kW to 3.4-4kW depending on the laser power used, the idling of the laser is causing a constant power draw at 2.1kWh.


Experiment D
Power [VA]
5000
0
1000
2000
3000
4000
5000
6000
7000
Action
Laser 1
Laser 2
Chiller 1
Chiller 2
PCW Flow [l/min]
100
50
Action
Flow In
Out Laser
Out Table
Temperature [°C]
21
20
19
18
Action
Temp In
Temp Laser
Temp Table
Gas Flow [l/min]
Time [s]

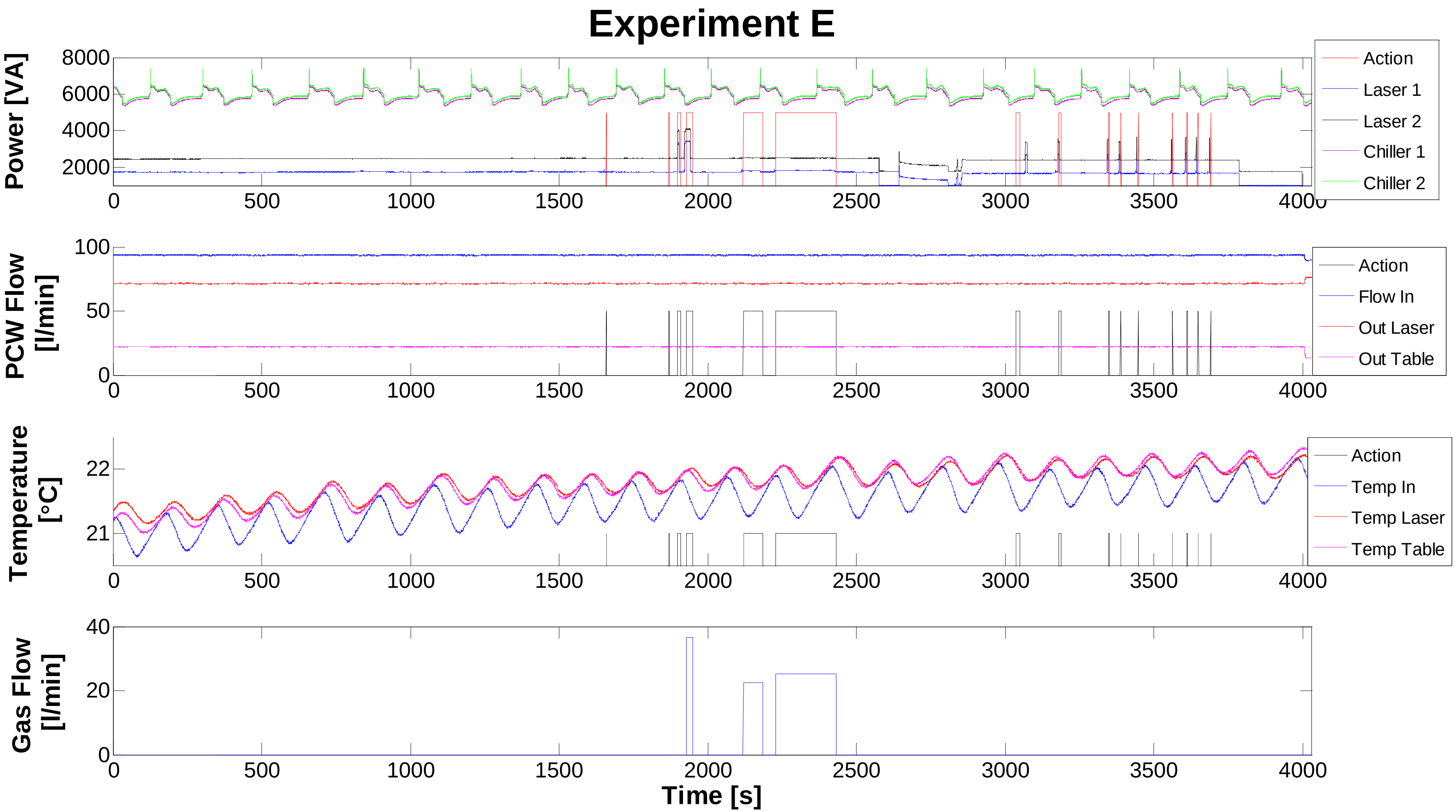


Figure 4-14: Comparison of consumption profiles (Experiment D and E)

The chilling circuit and its power consumption is the worst in terms of processing to idling, with no tangible difference to be observed, with Experiment A averaging 8.18 A, and experiments B-E at 8.36, 7.05, 7.55 and 8.49 A respectively. Additionally, the chilling circuit is constantly on, even if laser and controller are completely switched off, to avoid sedimentation and overall deterioration of the system – in terms of pump and the fluid used. As it is exclusively used by the laser, in reality its electrical consumption contribution should be a lot higher to account for the hours running when the laser is idle or switched off. At an estimate usage of 10 hours per week at an average 5.5 kWh, 158 hours at 5.5 kWh need to be accounted for in the environmental balance. If this was distributed/added to the baseline chiller consumption, a value of 92.4 kWh would be more reflective of the chiller electrical consumption per working hour. As such, it becomes clear that the flow volume of the closed-circuit chiller liquid is not as important as the electrical power consumed by its pumping and chilling system, as well as monitoring of the temperature to correlate higher electrical consumption (subtle in the chilling circuit data) with tool action. Additionally the surrounding temperature of the chiller might have a marginal effect on the power required.

4.4.1 Potential for Reductions

Close examination of Table 4-3 to see if there is potential for improvement, highlights that there are very few direct optimising opportunities. The action of laser and controller cannot be changed, similar to the laser gas consumption. The purge gas pressure, at least for this mode of operation, is already below the specified limit. With an increased pressure to 3.8 bar and the same weight loss, it would be consuming 11.84 l/min down from 22.5 l/min and with an increased pressure (3.8bar) at the same flow rate as calculated above (22.5 l/min), the weight loss would be at 2.34 g/s as against 1.23 g/s currently measured.

The chilling circuit could potentially be optimised to reduce the electrical load, although it is already placed outside the building and in free flowing air to allow maximum passive cooling potential. The replacement of the chilling fluid with a higher performing refrigerant, from the currently used water and glycol, could be an option even though this new refrigerant could have a much higher environmental impact. Additionally a different chiller system with a higher coefficient of performance could be used, but again the environmental impact of this change is questionable against the gain in performance.

Chapter 5 A New Holistic Framework for Environmental Footprint Assessment and Optimisation

5.1 Introduction

Detailed evaluation of supply chain management highlights that every consumable creates a footprint on the environment, starting with its sourcing and ending with its disposal. In traditional life cycle methodologies, such as ISO 14000, the footprint is established by following the product from cradle to grave. However, in complex manufacturing system, where production tools consumptions vary very little with different products produced, it is more logical to follow each consumable from its sourcing, through usage and eventual release back to the environment as these are directly impacted by the production tools.

5.2 Three Stages of Consumable Environmental Impact

This makes the assessment of environmental impacts almost independent of the products, i.e. only minor changes occur in the total values established due to different products. Additionally, the factory owner can see clearly where the factory's active contribution lies in terms of the total environmental impact, and how much passive impact is created up and downstream of the factory. Therefore, there is a logical split in the environmental impact contributions, which can be used to obtain a more standardised and transparent assessment methodology. A split into three distinct areas is proposed in this thesis, which encompasses the three major areas where environmental impact is added to the consumable. This proposed new assessment methodology is presented in Figure 5-1.

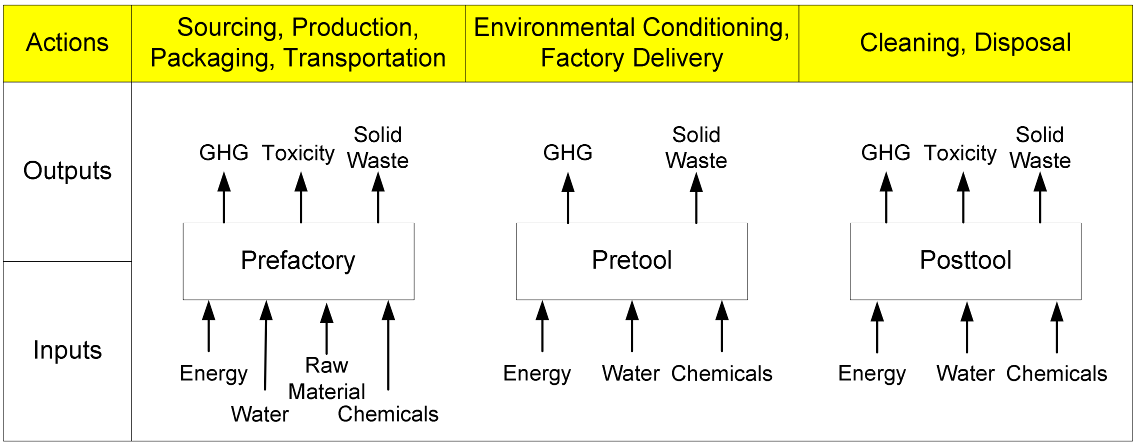


Figure 5-1: Three steps for holistic environmental footprint determination

The three impacts of each consumable are as follows:

1. The Prefactory Impact (PREF) follows the sourcing and production of the consumable to its delivery to the factory gate. This is a cradle to gate analysis.

2. The Pretool Impact (PRET) accounts for the footprint created by conditioning and delivering the consumable to the production tool within the factory walls. This is a gate to gate analysis.

3. The Posttool Impact (POST) accounts for the emissions, wastes and by-products created in the tool during processing and their treatment and release to the environment. This is a gate to grave analysis.

The environmental footprint is based on 1 kg or 1 kWh of consumable entering the production tool, meaning that the pretool stage is always based on 1 kg or 1 kWh of consumable. Therefore, sometimes a ratio is introduced where more than 1 unit of consumable is needed in the prefactory stage to make up 1 unit arriving at the production tool, especially in high purity / filtering systems. If for example 5 kg of consumable are required to produce 1 kg of usable consumable at the production tool, then this ratio needs to be included in calculations, meaning that the prefactory impact gathered has to be multiplied by this ratio in order to obtain a true picture of the environmental impact. This example is shown in Figure 5-2.

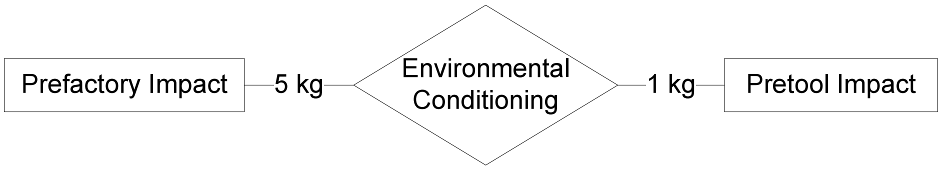


Figure 5-2: Compounding impact due to environmental conditioning in a factory

Additionally, if usable by-products exist, their proportional impact gets removed from the prefactory and pretool impact. For example in the generation of Nitrogen, Clean Dry Air is generated as a by-product and can be used at a different point in the factory.

5.3 Determination of Footprints

As mentioned in the Literature Review, the estimation of environmental footprints from long lists and requirements (e.g. LCA, TEE) can be very complicated and selective, i.e. it is highly dependent on the practitioner. Therefore, an interpretation of this data has to be included in order for the methodology to succeed and enhance the visibility and understanding of the presented data. KPIs are required that present the most important environmental considerations to the reader. However, these must to be standardised, consistent and transparent in their calculation and sources.

5.3.1 Prefactory KPI Development

The prefactory impact is the least manipulable and controllable impact from a factory point of view. Therefore, it is important that its development and establishment is standardised. Using an international LCI (Life Cycle Inventory) database as a starting point ensures that data is at least somewhat comparable, and more and more of these databases have been established by national and international groups and panels [90, 91]. The European Commissions' Life Cycle Inventory(ELCI) [92] database was used to calculate the KPIs in this study. It supplies 62 Inputs and 338 Outputs for each listed consumable, of which 337 are standardised and one is the desired consumable in kg or kWh. A selection of inputs and outputs is shown in Table 5-1. In the last two column of the first row *(process water, 1kg)*, the useful output from the LCI is shown. The inputs columns show the amount of energy and consumables being used in the consumable production process, and the output columns show the waste, in terms of heat, mass and radioactivity created by the process.

Table 5-1: Sample inputs and outputs for Process Water from [92]

INPUTS			OUTPUTS	
Consumable	**Resulting amount**		**Output / Waste**	**Resulting amount**
Air	0.111122703521308 kg (Mass)		*process water; ion exchange; production mix, at plant; from surface water*	1 kg (Mass)
barium sulfate	1.28635214609 26E-16 kg (Mass)		*calcium fluoride; reactor fuel assembly supply; production mix, at plant; low radioactive*	4.68056489678879E-9 kg (Mass)
Barite	3.39878651221379E-6 kg (Mass)		*demolition waste (unspecified)*	1.12810321648072E-5 kg (Mass)
Basalt	9.07823830316407E-7 kg (Mass)		*highly radioactive waste; reactor fuel assembly supply; production mix, at plant*	1.39679718949902E-8 kg (Mass)
Bauxite	5.74463724708556E-8 kg (Mass)		*medium and low radioactive wastes; reactor fuel assembly supply; production mix, at plant*	1.64307735145896E-8 kg (Mass)
Bentonite	1.38940090325202E-6 kg (Mass)		*overburden (unspecified)*	0.01591611648305 kg (Mass)
biomass; 14.7 MJ/kg	3.73288717434634E-11 MJ (Net calorific value)		*plutonium as residual product; reactor fuel assembly reprocessing; production mix, at plant*	2.75458848328279E-11 kg (Mass)
brown coal; 11.9 MJ/kg	0.0114331110303846 MJ (Net calorific value)		*radioactive tailings; reactor fuel assembly supply; production mix, at plant*	8.19914984331506E-6 kg (Mass)

Additional information about the specific data collection of each consumable is supplied on the website as shown in Figure 5-3. It defines the collection area (Point 1) from which the averages were obtained, e.g. EU-27, and the exact processing steps used in the evaluation (Point 2).

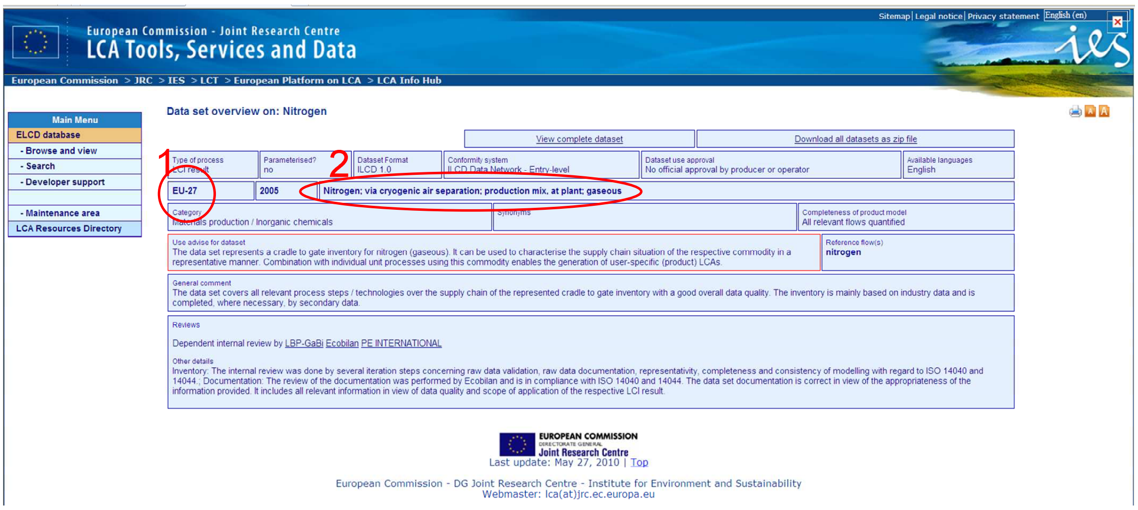


Figure 5-3: Screenshot of detail supplied for LCI on website [92]

Even though production methods used to obtain the consumable could vary or the geographical location may not be 100% correct, it still gives a good estimation of the consumables impact. However, due to the large amount of information supplied, there is no clear overview possible of the actual impact of each input and output listed. Therefore, grouping is necessary to allow easy interpretation for each consumable's impact between sourcing and production stage.

Currently, the ELCI does not estimate transportation and packaging impacts. These KPIs will have to be introduced from a different database at a later stage. Additionally, due to global production in most companies and suppliers, it is increasingly difficult to estimate these two inputs accurately. For the moment, no satisfactory database exists to calculate these generically, therefore, if it exists, actual factory data should be used.

From the ELCI, some direct KPI categories can be determined. This might involve some grouping within inputs or outputs, for example different water sources, such as ground and surface water are combined to give the overall water input. Using these combinations for the input data, total input weight [kg], water amount [kg] and grouped input energy [kWh] are evaluated. Similarly, waste weight [kg], waste energy [kWh] and total radioactive material [kBq] are easily accumulated from this output data.

Additionally, different external categories can be applied, comparing the chemicals listed with databases for GWP or toxicity to give an even more holistic picture of the environmental impact of the consumable. For this method, the CO_2 equivalent for all greenhouse gasses was found and summed up.

For this research, five final KPIs were chosen that define the prefactory stage.

1. The weight factor: Using total input weight and total output weight, this shows how much waste is created for 1kg or 1kWh of consumable. Assuming that not all materials are used up into the production of the consumable, the addition of the two gives the amount of waste created, as it reduces available resources (inputs) and adds mostly unusable wastes (outputs). Subtracted from this is the amount of water in as this is used in a separate KPI. Additionally, if the consumable is weight based, 1kg is deducted from this value as this is the useful output (as described in Table 5-1).

$$WASTE = (Input\ Weight - Input\ Water) + \ (Output\ Weight - 1) \qquad (5.1)$$

2. The energy efficiency: the amount of energy supplied in divided by the waste energy discharged shows the energy efficiency of the process. Of course the overall volume of energy is also important and should be introduced as a separate KPI in future revisions.

$$ENERGY\ EFFICIENCY = \frac{kWh\ in}{kWh\ out} \tag{5.2}$$

3. The water ratio: How much water is affected by the process and thus not available for the environment.

$$WATER = Water\ in \tag{5.3}$$

4. The radioactivity: The amount of radioactivity (in kBq) created, summed up from the output list.

$$RADIO = \sum_{i=1}^{n} Radioactivity\ (i) \tag{5.4}$$

5. The Global Warming Potential: A match between the output list and a list of GWP to see the total GWP based on a 100 year decay horizon and then converted to million metric tonnes CO_2 equivalent.

$$GWP = \sum_{i=1}^{n} Global\ Warming\ Gasses\ (i) * Weight(i) \tag{5.5}$$

These KPIs are then summed up un-weighted to yield the new PREF number.

$$PREF = WASTE + ENERGY\ EFFICIENCY + WATER + RADIO + GWP \tag{5.6}$$

5.3.2 Pretool KPI Development

The pretool stage is the most controllable by the factory owner, as it fully occurs on the factory site. Dependant on which supply systems are used in the factory, the pretool impact can vary considerably. For its calculation, factory systems and data are required. Because pumps, filters and other preparatory stages supply consumables directly to the production tool, they are most focussed on. Questions asked to find this data are for example: How much energy is used in each pump to deliver the consumable? Are the pumps water cooled, if so how much PCW is the pump using? How much of the consumable is rejected in filtering and pumping?

Again, these factors need to be grouped to allow an easier overview and analysis of the consumables path. Of course, for in-house prepared consumables, especially high purity ones such as Ultra Pure Water, this footprint is quite large. The final KPIs must allow for this as well as smaller impacts for less processed consumables. Currently two KPIs are used.

1. The energy consumed: Summation of pump energies, which is assumed constant unless FFUs are used, and energy used for heating/cooling. Of course there is a possibility for large energy losses due to inefficient systems themselves, but these are a concern after the optimisation of the production tool.

$$ENERGY = \sum_{i=1}^{n} Energy\ consumed\ in\ support\ systems\ (i) \tag{5.7}$$

2. The waste weight created by filters, slurry, or involuntary gas releases

$$WASTE = \sum_{i=1}^{n} Wastes\ created\ (i) \tag{5.8}$$

3. The ratio of rejection: if a consumable has to be conditioned and hence only a fraction of the originally delivered consumable is usable, this must be taken into consideration

$$REJECTION = \frac{Weight\ consumable\ in\ (= 1kg)}{Useful\ weight\ out} \tag{5.9}$$

This sums up into the new PRET number

$$PRET = (ENERGY + WASTE) * REJECTION \tag{5.10}$$

5.3.3 POST KPI Development

The accounting for tool emissions, be they solid wastes, gases or liquids, is only partially in the control of the factory owner. Due to environmental control and emission restrictions and regulations, certain emissions need to be treated, e.g. diluted, before their release to the environment. With increasing regulation, this aspect of the holistic assessment is becoming more important and hence increases in size.

To determine this footprint, factory systems data is used, as well as chemical reaction knowledge to determine the by-products produced and thus allowing their environmental impact assessment. It thus focuses on the emissions and their treatment (for alleviation) before release. This means e.g. filters, scrubbing and heat removal from the system.

The final sample KPI chosen try to encapsulate this. Of course, release to the environment also means possible contamination such as causing eutrophication or toxicity to humans, animals or general environment. An expansion of these into KPIs is probably the most valuable, but beyond the scope of this proof of concept.

1. The energy required in filtering, scrubbing and pumping of the consumable.

$$ENERGY = \sum_{i=1}^{n} Energy\ consumed\ in\ treatment\ systems\ (i) \quad (5.11)$$

2. The Heat removed from the process.

$$HEAT = \sum_{i=1}^{n} \Delta Temperature * Time * Flowvolume \quad (5.12)$$

3. The waste out in terms of kg.

$$WASTE = \sum_{i=1}^{n} Wastes\ created\ (i) \quad (5.13)$$

- The GWP from emissions.

$$GWP = \sum_{i=1}^{n} GWP\ Gas\ (i) * Weight\ Gas\ (i) \quad (5.14)$$

Thus the new POST impact is calculated as:

$$POST = ENERGY + HEAT + WASTE + GWP \quad (5.15)$$

Therefore, to obtain a full environmental impact of the consumables, the three footprints are then added to give the new total environmental impact:

$$Environmental\ Impact = PREF + PRET + POST \quad (5.16)$$

5.4 Weighting and Normalisation of KPIs

The KPI values used in the three calculations (PREF, PRET, POST), although being reported in different units like kg, kWh or kBq or as ratio, are currently treated as equal without requiring conversion. This, however, causes certain KPIs to be much more dominant, for example the Radioactivity KPI which has no maximum limit vs. the energy efficiency KPI, which can only vary from 0 to 1. There are two ways to overcome this problem in future revisions.

One is to find conversions for each unit into each other, similar to the ECF's in the S23/TEE guideline. This would mean that direct values would be comparable. The other method would be to find normalised scales for each unit. This would mean setting a scale from 0-1 or 0-100 for each KPI, with 0 equalling 0 in the original scale and 100 equalling the highest impact imaginable. This method has the advantage that future KPIs which might have yet again other units associated with them could be more easily incorporated, as well as balancing the different KPIs against each other much better. For further discussion of this sensitivity issue and the normalisation see Section 5.7.2, which discusses the impacts of changing radioactivity values and global warming potential values. The KPIs currently chosen only represent a sample of how these values should be chosen and how to approach their calculation.

5.5 Visualisation of Environmental Footprints

Although the three footprints in themselves are already more understandable, it is necessary to combine the three to allow overall optimisation with respect to all environmental harmful stages. This means that a balancing of the three impacts for each consumable is required for a holistic optimisation.

If each partial impact is taken in an isolated view, different consumables may present themselves as the main focus for optimisation at each stage. However, this might worsen the upstream or downstream impact of the consumable, or have a negative effect on other consumables used within the same stage. Only if the three impacts are combined into a full holistic impact, and inter-utility relationships are known can a full environmental assessment and optimisation take place. In Figure 5-4, a sample visualisation is shown.

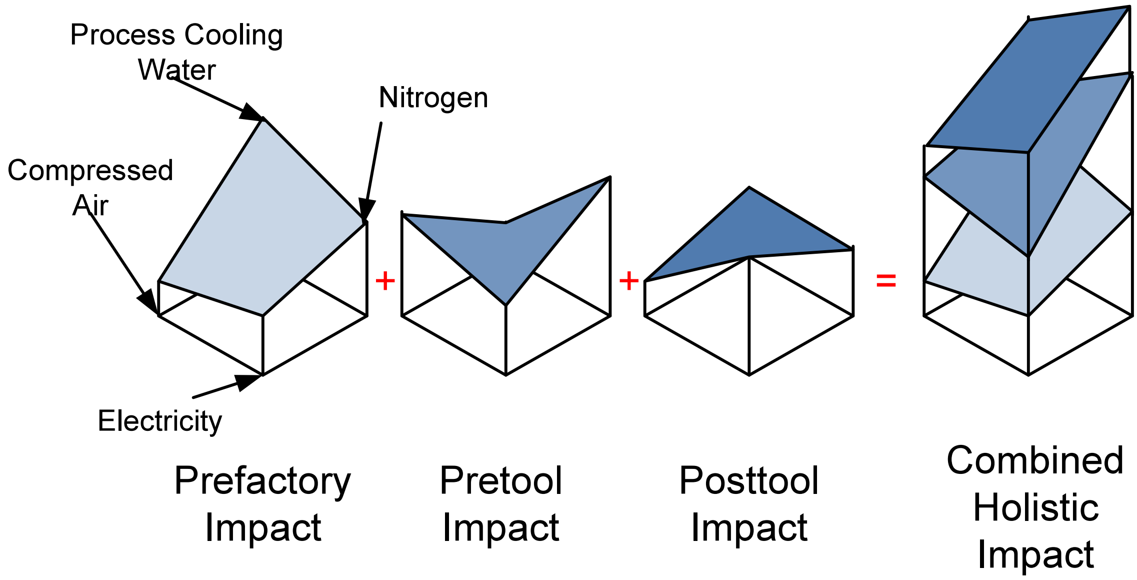


Figure 5-4: Graphical representation of holistic environmental data

For this, all consumables used in a production tool are placed on equidistant corners of an area, in this case a square, like a spider diagram. The value of each consumables separate stage impact is then added as the height at that corner, for example 2, 4, 6 and 8 for Compressed Air, Electricity, Nitrogen and PCW respectively. When these points are connected, a volume is formed which represents the overall stage environmental impact of that production tool, and the objective is to optimise this overall volume. This is repeated for each stage, and then the three impacts are combined to give the holistic impact. This is shown in Figure 5-4.

This means that all three impacts are put into perspective of the overall volume, and it means that this overall combined volume is to be optimised. That may mean decreasing one and increasing another consumable, but always with overall minimisation in mind.

5.6 Sample KPI Population for the Laser

As described in Chapter 4, four consumable supplies exist, which have varying degrees of conditioning and consumption. These values will be emphasised by the KPIs calculated. The calculations for each stage and the challenges faced are described below.

5.6.1 Prefactory Impact

From the LCI database, the PREF KPI were extracted, first manually in an excel sheet and then automated in a Matlab program based on the MS Excel sheet, as shown in Appendix F, to allow for easy calculation for any consumable. The return from this Matlab program is shown in Table 5-2.

Table 5-2: KPI and Prefactory impact returned from Matlab program

Consumable	Weight IN [kg]	Energy IN [kWh]	Water IN [kg]	Waste Weight [kg]	Waste Energy [kWh]	Total GWP [mt CO_2]	Radioactivity [kBq]	Check unit and convert	Prefactory Impact [ ]
Electricity	20.11	3.09	12.55	9.49	2.95	8.7E-10	7.34	0.00	37.90
Process Cooling Water	1.35	0.02	1.22	0.06	0.01	6.5E-12	1.95	0.00	3.88
Nitrogen	3.68	0.50	1.51	1.44	0.32	8.8E-11	62.27	0.00	68.03
Compressed Dry Air [m^3]	2.21	0.48	1.46	1.01	0.31	8.5E-11	60.19	1.00	64.04
Compressed Dry Air[kg]	0.27	0.06	0.18	0.12	0.04	1.0E-11	7.23	0.00	7.70

Whilst the gas actually used in all experiments was Argon, there is no LCI database entry for this gas. However, the extraction of Argon from air follows the same process as the extraction of Nitrogen. Therefore, the LCI for Nitrogen was used, whilst all consumption data is still calculated from Argon, for example in terms of molecular weight for the flow calculations.

The problem with the Compressed Dry Air is that it is currently in m^3 volume in the LCI database, so has to be converted to kg first to be comparable to the other consumables. This problem is indicated by the Matlab program with a '1' in the second last column as seen in Table 5-2. With this conversion[1],using the universal gas law, the final prefactory impacts for the four consumables are determined as:

5-3: Calculated Prefactory Impacts for the Laser

Consumable	Prefactory Impact
Nitrogen	68.03
Electricity	37.90
Process Cooling Water	3.88 (0)
Compressed Dry Air	7.70

The PCW value here refers to PCW if it were delivered to the factory continuously. However, since the PCW in the laser chilling circuit is in a closed loop and pumped continuously, this prefactory value should be zero, indicated by the (0) in the table.

5.6.2 Pretool Impact

The pretool impacts are not very pronounced for the consumables used in the laser as there is very little environmental condition done to any consumable. A breakdown of the consumable conditioning occurring in the laser is as follows:

1. For the Nitrogen and Argon, there is no conditioning as they are supplied straight from the gas bottle to the tool.

[1] Compressed Dry Air @ 7 bar, $1m^3$ volume
Molecular Mass of Air: 28.97 $gmol^{-1}$
PV = (m/M)RT
w = (700000*1*0.02897)/(8.314*293.15) (at 20C)
w = 8.32 kg = $1m^3$ compressed dry air
therefore **divide obtained value by 8.32** to get prefactory impact for 1kg air

2. The electricity is not conditioned at all. Any system losses could be included here to constitute part of the pretool impact. However, none were found here. If, for example, power factor correction takes place the waste from this would be included.

3. The laser gas (CO_2), as it is integral to tool functioning is disregarded, even if some conditioning may occur within the laser tool itself.

4. Although the real consumption values for the air compressor and pump are unknown, an equivalent pump is found in the workshop (predating the centralised supply system used now) with a plate rating of 7.5 kW, therefore the pretool impact used in this case for Compressed Dry Air is assumed at 7.5.

5. For the PCW a small filter exists but the exchange rate is very long, i.e. long time between changes (years), and is hence disregarded. The chiller electricity consumption needs to be included. The chiller draws an average of 8.18A, and hence the apparent power can be calculated as 5.5kWh.

Using the system data described above, the following results for the pretool impact were found:

5-4: Calculated Pretool Impacts for the Laser

Consumable	Pretool Impact
Nitrogen	0
Electricity	0
Process Cooling Water	5.5
Compressed Dry Air	7.5

5.6.3 Posttool Impact

The posttool impact again is quite small as there is little waste or decomposition of materials in the laser cutting process.

1. The heat removed from the process by the PCW (monitored with the thermocouples) gives a HEAT value of 5.708 kWh[1] for the PCW.

2. An exhaust volume of 250m^3/h is used to ensure no splatter or decomposed gases are fed into the environment to affect the operator nor affect the focussing lens. With a plate reading of 400V and 2.5A, 1kWh is calculated. This is added to the posttool impact of Nitrogen/Argon, as this is mainly used for the protective gas of the laser and lens.

3. The few splatters of material (mainly melted metal) are caught below the samples and are not removed as this is a very small volume.

Therefore the posttool impacts are as follows:

5-5: Calculated Posttool Impacts for the Laser

Consumable	Posttool Impact
Nitrogen	1
Electricity	0
Process Cooling Water	5.7
Compressed Dry Air	0

[1] Heat removed = Mass flow-rate * specific heat of fluid * temperature difference
= (0.082[m^3/min]*60[min]*997.7735[g/m3]*1000)*4.186[joule/g°C]*1[°C]
= 4909046*4.186*1
= 20549265 joule/hr
= 5.708 kWh

This allows the calculation of the overall environmental impacts are as shown in Table 5-6. From this, the difference between in-house produced and delivered consumables becomes clearer: Whilst Electricity and Nitrogen have a high prefactory impact, there is very little conditioning required in-house, the PCW and the Compressed Air require conditioning or delivery in the factory/ workshop.

For example, Electricity has a high prefactory impact, but requires neither in-factory conditioning nor any treatment for by-products. Hence its total impact is equal to the prefactory one. In contrast, the PCW starts with a relatively low prefactory impact (or 0 if considering the closed circuit of it), but requires constant conditioning via the chiller - represented in the pretool impact – and requires alleviation of the heat burden in the posttool impact.

Table 5-6: Total environmental impacts for all Consumables

Consumable	Prefactory		Pretool		Posttool		Total Impact
Electricity	37.90	+	0	+	0	=	37.90
PCW	3.88 (0)	+	5.5	+	5.7	=	15.08
Nitrogen	68.03	+	0	+	1	=	69.03
Comp. Air	7.7	+	7.5	+	0	=	15.21

5.6.4 Visualisation of Laser Environmental Footprints

For the stage impacts calculated for the laser, the different impacts are shown in Figure 5-5. This is done in scale so that volumes shown are proportional to the values shown in Table 5-6. This shows that the Nitrogen dominates the environmental impacts, whilst the PCW has the smallest impact. It also can be seen that there is very little conditioning in the factory (pretool impact) and very little harmful emissions (posttool impact).

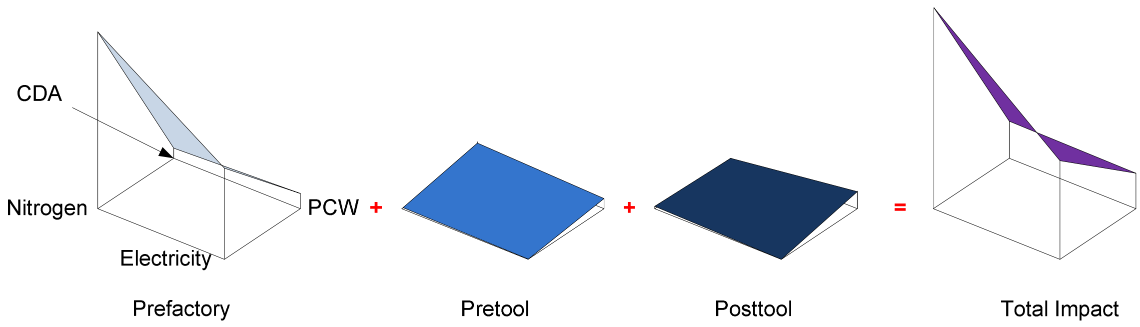


Figure 5-5: Actual impacts for consumables used in laser

5.7 Practical Application

From the investigated methods used in the Literature Review, one of the most problematic points was that they are based on static data. However, for a true optimisation of the tool, its dynamic behaviour is of most importance. Another problem was that 100% coverage of consumable supplies and subsystems is required in these methodologies. However, as found in the experimentation with the industrial partner, this is not feasible in a running, complex manufacturing factory.

Therefore, it is important that a focus for the measurement is defined. This has to be based on the environmental impact of the consumables. This research proposes a selection aim of covering 90% of the volumes and environmental impact created by the production tool. It is also important that there is the minimum amount of measurement and or calculation involved to determine these values. Therefore, it is proposed that the multiplications of the prefactory impact and the manufacturer consumption guidelines, or values from rate plates, are used to determine these Decider values.

The prefactory impact is easily obtained for most consumables, and most production tools come with recommendation guidelines for minimum or maximum flows and requirements. For in-house produced consumables, the pretool impact is used instead.

Using these impacts has the advantage that they give a good overview of the expected complexity of the consumable used. If a large prefactory impact exists, it indicates a high purity or complex sourcing methods. Similarly, if a large pretool impact exists, it indicates that a lot of conditioning occurs within the factory. Combining this with the expected flow rates means that a balancing of high volume, low impact and low volume, high impact consumables occurs. The calculation is shown in the equation below.

$$DECIDER = \sum_{i=1}^{n} Flow\ volume(i) * PREF(i) \tag{5.17}$$

Table 5-7: Calculated Decider values for Laser

Consumable	Consumption	Pre-factory	Decider Value
PCW [l/min]	70	3.88	**271.60**
Compressed Air [l/min]	0.0025	7.7	**0.02**
Nitrogen [l/min]	4	68.03	**272.12**
Electricity [kWh]	20[1]	37.9	**758.00**
Total Decider Value			**1301.74**
90% Limit			**1171.57**

For the practical example of the laser, the manufacturing data (see Table 4-3 above), was used as well as the prefactory data calculated. Of course, as the consumption values are estimated, a margin for error exists. The Decider values are shown in Table 5-7.

These calculations show the balancing of the impacts and the consumption rates quite clearly: whilst the PCW has a high consumption and a low environmental impact, the Nitrogen is the exact opposite with a low (theoretical) consumption and a high environmental impact, so much so that the two Decider values calculated for the consumables only differ by less than one.

[1] faceplate value of 400V (x3) and 50A equals 20kWh

Table 5-8: Calculated Decider values for Laser with increased PCW value

Consumable	Consumption	Pre-factory	Decider Value
PCW [l/min]	70	92.5	**6475.00**
Compressed Air [l/min]	0.0025	7.7	**0.02**
Nitrogen [l/min]	4	68.03	**272.12**
Electricity [kWh]	20	37.9	**758.00**
Total Decider Value			**7505.14**
90% Limit			**6754.63**

However, as briefly discussed at the end of Section 4.4.1, the pretool impact of the PCW is much higher if the actual data is used versus the ELCI prefactory data, which is based on an open loop PCW supply rather than the closed loop existing in the workshop. Therefore, if using the new pretool impact for the PCW, and looking at the newly calculated Decider values as shown in Table 5-8, it is clear that the PCW widely dominates the environmental consumption.

If looking at both tables, it becomes clear that the compressed air is the least impacting consumable, in terms of theoretical consumption rate and prefactory impact. In fact, only 0.0015% of the overall total theoretical impact are attributed to it, so it is not going to be measured or monitored with very little detrimental effect on the overall validity and significance of the results.

5.7.1 Combining Measurements and Impacts

After using the Decider to determine the to be monitored consumables, and obtaining their consumption behaviour through measurement, the overall environmental consumption behaviour of the tool can be found.

Figure 5-6 shows a sample environmental impact for all consumables for the duration of the measurement. It shows that the purge gas impact is peaking the highest, whilst the laser impact is consistently the smallest value. Most constant and second highest is the

PCW consumption. Average values of the three consumables were 1051, 1134 and 87 for gas, PCW and electricity respectively. This shows that the PCW flow is highest overall if averaged out over the entire processing time, and would be again higher if only the action was taken into account.

It again shows the importance of balancing the consumable volumes with the consumable impacts, as otherwise the significance of that consumable might be lost. It also shows that the Decider values were right in their predictions of Gas and PCW being the consumables with the most impact and being quite close together in final values.

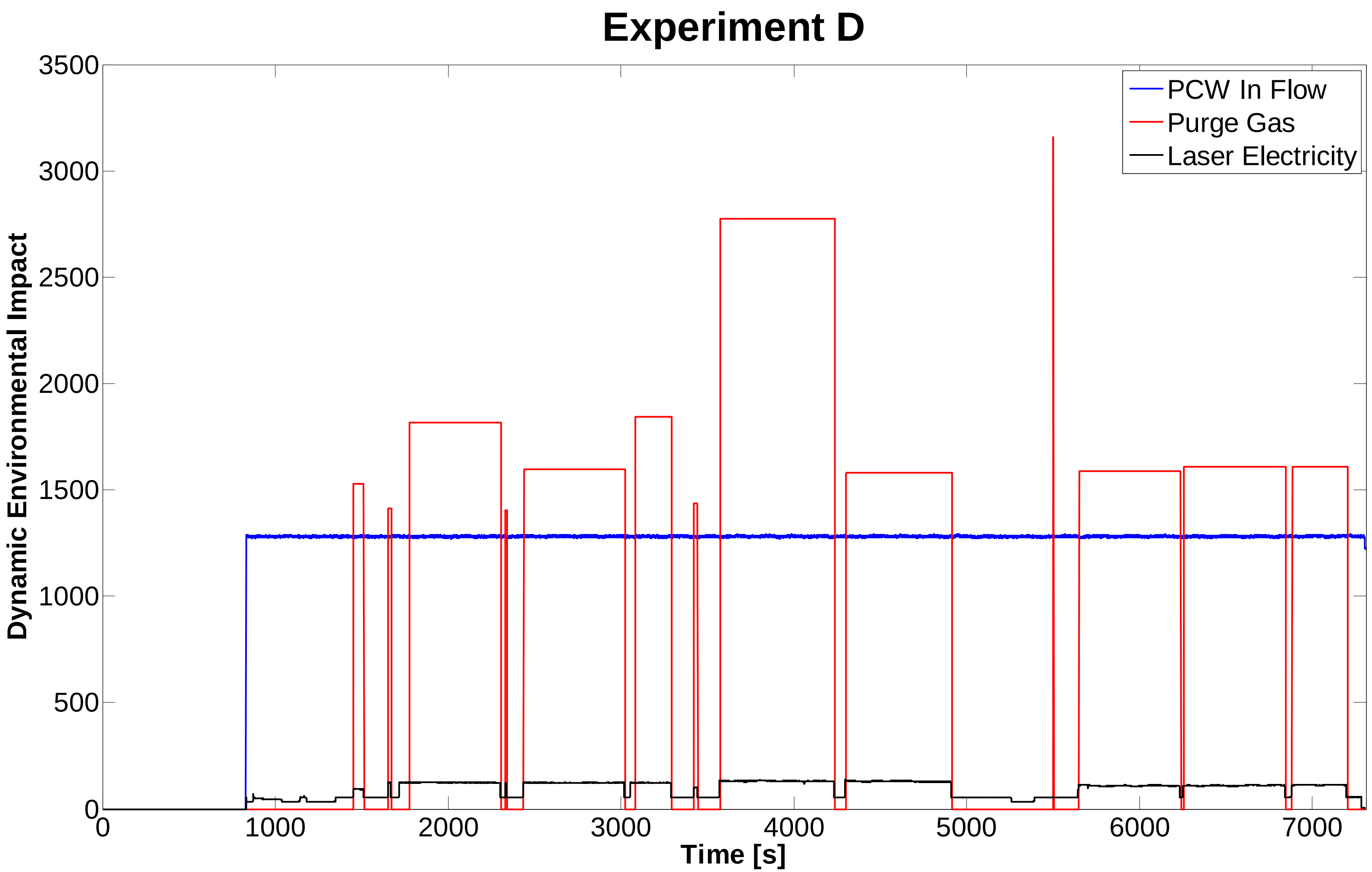


Figure 5-6: Dynamic environmental impact consumptions of Laser (Experiment D)

5.7.2 Analysis of KPI and Impact Sensibility

When looking at the determining factors for the total environmental impact, as shown in the top part of Table 5-9 (Original Calculations), it can be seen that the radioactivity has the highest influence on the impact values, coming from the prefactory impact.

Table 5-9: KPIs and Impacts for all consumables

	KPI or Impact	Electricity [kWh]	Process Cooling Water [kg]	Nitrogen [kg]	Compressed Air [kg]
Original Calculations	Waste [kg]	17.06	0.20	3.61	0.21
	Energy []	0.96	0.51	0.64	0.08
	Water [kg]	12.55	1.22	1.51	0.18
	Radio [kBq]	7.34	1.95	62.27	7.23
	GWP [Mt]	0.00	0.00	0.00	0.00
	Prefactory []	37.90	3.88	68.03	7.70
	Pretool []	0.00	5.50	0.00	7.5
	Posttool []	0.00	5.70	1.00	0.00
	Total Impact – Original []	37.90	15.08	69.03	15.21
Calculating Prefactory Impact without Radioactivity	Prefactory without Radioactivity []	30.56	1.93	5.76	0.46
	Total Impact [] without Radioactivity + GWP [kg]	30.56	13.13	6.76	7.96
Changing the GWP unit (Prefactory)	Prefactory with GWP [kg]	38.77	3.88	68.12	7.71
	Total Impact - changed GWP []	38.77	15.08	69.12	15.21
Changing the PCW Pretool Impact	Pretool with changed Chiller []	0.00	92.40	0.00	7.5
	Total Impact [] changed Chiller + GWP [kg]	38.77	101.98	69.12	15.21

If this KPI value was removed from the calculations and only the remaining ones were used, the data would change as shown in following two rows of Table 5-9 (Calculating Prefactory Impact without Radioactivity). When this is done, the Nitrogen impact drops by a factor of ten, which means its overall impact is now almost at the same level as the electric consumption, as shown in Figure 5-7. Over time, the gas impact averages at 100, with an average processing value at 150. The electric impact averages at 69, with an average processing value of 106. Now, the PCW is the most dominant consumable, as it is least affected by this change in KPI.

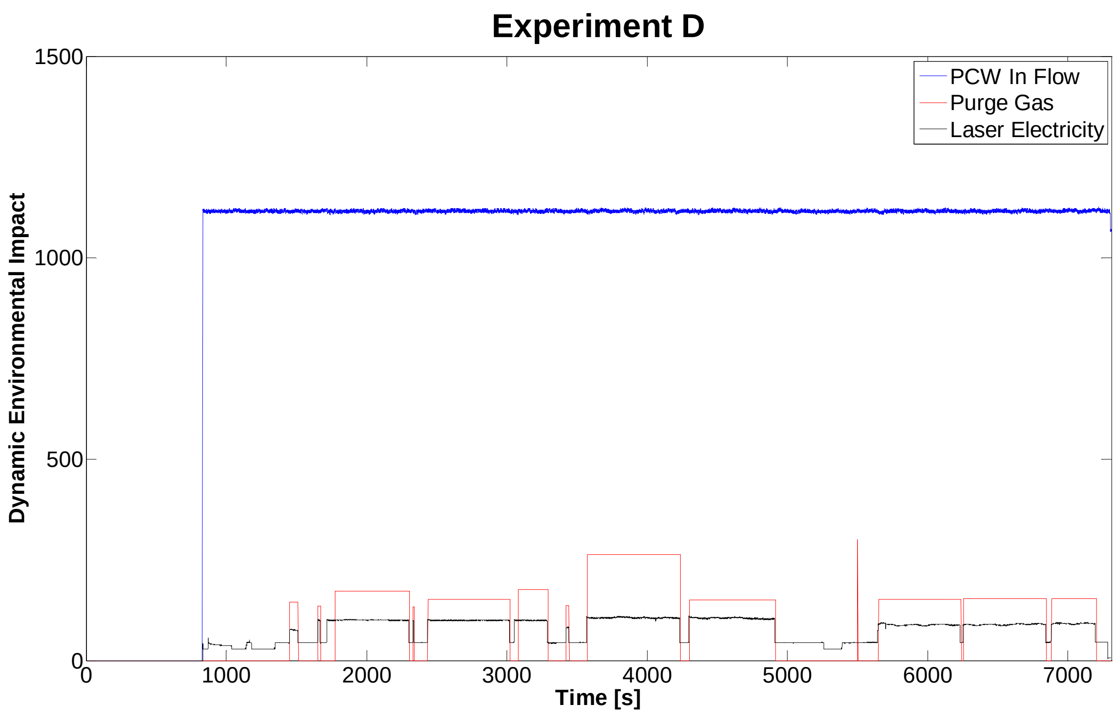


Figure 5-7: Total environmental consumption without radioactive KPI (Experiment D)

If the smallest KPI, in this case the GWP, is converted to kg instead of Mt, as shown in line 13 and 14 in Table 5-9 (Changing the GWP unit), it still has very little influence on the overall result. However, the GWP is an important aspect so it does require a weighting factor in order to reflect its real influence.

Additionally, if the constant chiller consumption over 24h is divided and added to the PCW pretool value as shown in lines 15 and 16 in Table 5-9 (Changing the PWC Pretool Impact), the impact of PCW increases to 7683 (or 8681 if not including the downtime before processing) and means it dwarfs the purge gas value, as shown in Figure 5-8.

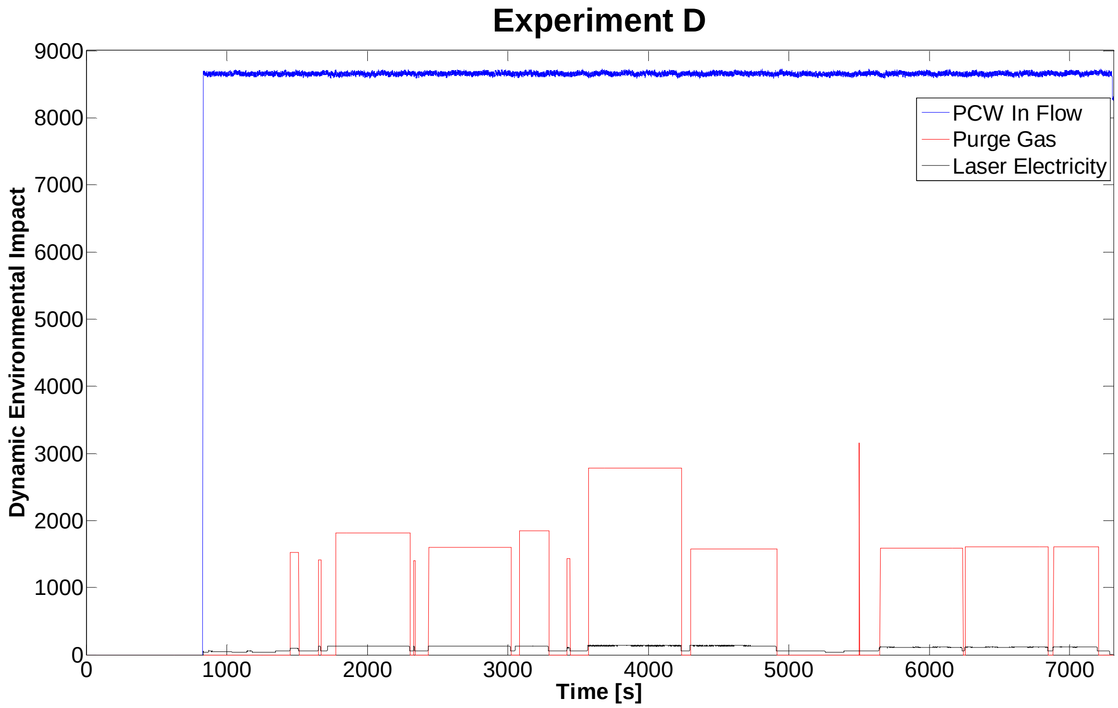


Figure 5-8: Environmental impact with modified PCW consumption (experiment D)

What these changes in environmental footprint calculations have shown is that it is not only necessary to use standardised values for the impact and dynamic consumption measurement to obtain a true picture of a tools environmental impact. But it is also required that the standardised values used are related to each other in such a way that high and low numbered KPIs are balanced to supply a normalised impact. This means that a conversion to a common unit should be investigated, i.e. a weighting process has to occur. This is especially dominant in the prefactory impact which is the only impact currently using several KPIs in the sample tool calculations. Balancing between the weight of CO_2 equivalent which is very small, and the radioactivity created of certain consumables which is much larger in value, but not necessarily in true environmental impact is important. For example, the human body emits around 4.4kBq over 10 days, and Uranium in its natural prevalent state emits around 25kBq/g (where Bq is a measure of dissipating atoms per second). So the value collected in the prefactory impact for radioactivity needs to be related to this information in order to obtain a true value. What would be desirable would be a ratio that would define weak, medium and high values of radioactivity. Similarly, the GWP value will have to be related to an average value so that its impact is not lost among the higher values collected, such as waste.

5.8 Online Tool KPI and Footprint Calculations

During the rollout of the TEE tool in the model factory, a lot of the subfab support systems energy, cooling and gas requirements were measured for each production tool in the factory. With this data, prefactory and pretool impacts can be calculated for some consumables shown in Figure 3-2. However, not always were consumable volumes given in this data, and very often only pressures were found.

As an example, the PCW supply flow rate to the mainframe is known, as well as the corresponding electrical power used in the chiller and any waste created in the system. From this, a PRET value of 72 can be calculated. The POST value can be found by calculating the heat removal as shown for the laser before, from which a value of 0.07 was obtained. The PREF value for this can either be 3.88 or 0, which mirrors the discussion of the laser PCW PREF value. Therefore the overall environmental impact of the PCW is 75.95. This is on a per minute rather than per unit base as the actual consumption volume is not known. If it is known the value will have to be adjusted accordingly.

Similarly, for the creation of the vacuum in the process chambers, the consumption rates of electricity, PCW and Nitrogen are known for each of the pumps, which are located at the bottom of the diagram. From this, a PRET value of 123 can be calculated. Additionally the PCW temperature difference is known, so a partial POST value can also be calculated (Partial because there is also an exhaust connected whose removal rate is unknown). This value calculates as 0.01. There is no PREF value since it is generated on site. The known cumulative impact is therefore 123.01. Again this is on a per minute basis rather than volume based. However, since volumetric measurement of vacuum is not possible, the number calculated on a time basis is much more representative.

From these examples, it can be seen that the PRET values can be easily calculated from the information that is provided by the rating plates of support systems or quick power measurements with clamp-on meters. Again, these are generally only an estimation of the PREF, as it can only be verified by actual measurements, but it will give a good starting point for the Decider values, which will in many cases also include the impacts of the support systems.

The inclusion of the support systems in the PRET impact is important for the inclusive approach of the method, as the support systems require 40-60% of the overall consumables in the factory itself, which was found in the literature as well as by the factory employees in subsequent resource efficiency projects. The attribution of subfab and support systems to the different consumables does increase in difficulty with more support systems and complex delivery systems. However, if approached methodically it is still simple to apply and the data collection effort is actually quite small for the initial Decider calculation phase. The usage of the Decider values and the subsequent selected measurement of the consumption rates show that it is simple to apply to complex tools and will return consistent results to the factory owner. It is also a lot more transparent for a reader to see how the data is manipulated and how values are obtained. For more complex tools, some ambiguity can occur at the Decider stage, where different consumable mixes could make up the final consumables to be measured, but as long as choices are documented and the reasoning behind them are given, transparency is still ensured and the choices are comprehensible.

Therefore, the ease of application of the method to complex manufacturing tools can be seen. The methodology stays simple although the system might be more complex. Since the calculation of the PREF value comes from the LCI database, and the PRET value can be estimated by the rating plates, the only more difficult calculation is currently the POST value, as there is limited information in the data supplied by the factory.

Chapter 6 Conclusions

6.1 Novelty of Research

This research addressed challenges associated with legacy production tool measurement and the accounts for their environmental impact. Three major topics were addressed during the course of this research:

1. The inclusion of the dynamic behaviour of the tool enables true optimisation in terms of environmental impact of the tool, and subsequently of the whole factory. There is a shift of the assessment focus away from product or factory towards the production tools and their support systems. This gives a focus and real targets for optimisation rather than having static values per product or factory which leaves little optimisation potential.

2. The use of KPIs (Key Performance Indicators) enables the environmental impact of the consumables used to be defined much more clearly and the split into three distinct areas of environmental impact creation shows exactly where it is created, who owns it and in which respect it could be optimised.

3. There is a consistent transparency in the method, covering environmental impact calculations, measurement selection and dynamic tool measurement. This means that values recorded or calculated are based on a simple method as well as allowing comparison of values across competitors.

Through the visualisation of the environmental impacts, both in 3D to show the dependencies between consumables as well as in 2D graphs, a simplistic start for optimisation is enabled.

This new method captures and visualises the environmental footprint of a legacy tool, which enables optimisation of the consumption rates. It holds true not only for semiconductor manufacturing industry tools but also for other industries, as the KPIs used encompass impacts that are required in the creation of most consumables, and the selection method for the measurements ensures consistent results for any production tool, be it simple or complex.

6.2 Detailed comparison of challenges and solutions

From the literature review and sample tool assessment, seven key challenges were found that showed gaps in existing methodologies and practices in terms of environmental assessment, and allowed room for ambiguity in the interpretation and collection of environmental impact data.

1. The complexity of methods themselves in terms of data collection demands and values provided, in combination with no clear guidance for action was a major deterrent in the adaptation of these methods. It left room for ambiguity in terms of collection, recoding and representation of the data. Conduction by layman was not possible due to the vast amount of requirements without practical guidelines given.

2. The transparency of why certain data is required, or where supplied data is coming from, is not given. Any instructions given are not clearly defined and allow different interpretation by different practitioners.

3. The shifting of environmental burdens upstream or downstream of the analysis area done (gate to gate analysis) enables hiding of the true environmental impact of the product or factory action, e.g. when importing substantially manufactured parts and only assembling them, means a small footprint is associated with that company, however, the much larger manufacturing footprint is ignored. Additionally, there is no regulation towards double counting of environmental impacts between suppliers and consumers, and if followed through, can either alleviate all blame onto the end consumer or onto the consumable supplier.

4. The data required and used in existing methods is largely based on static data, for example annual or monthly averages. Even if percentages for idling and processing are used, for example in the TEE tool, it still does not give a full overview of the dynamic behaviour of the tool.

5. Due to many assessments being product based, the real focus of factory / production impacts are lost. Because they give values for the products impact, and use static factory data for e.g. electricity or gas consumptions, they do not enable the factory to look at their own consumption optimisation potential, and it means there is no granularity within the data to attribute to high value processes.

6. Because often the focus is on one consumable, there is a chance that impacts get shifted between consumables. If the consumable in focus is reduced, others

might increase which may have a much higher environmental footprint associated with them.

7. There is very little existing instrumentation on legacy tools, which makes direct measurement difficult. Additionally, in complex manufacturing, intrusive measurement is difficult because of its potential to introduce impurities into the systems. It is also very difficult to find invasive, and even more so non-invasive, measurement devices that are suitable for volume and pressure as well as the line size. Especially with decreasing line sizes, it is impossible to measure accurately or measure at all.

The method introduced by this research addresses these points as follows, allowing for a much more practical and transparent approach.

1. Due to the introduction of a three staged impact assessment and the clearly defined KPIs for each of them, any uncertainty towards which impacts to include or exclude is removed. Additionally, it leads to a reproducible and traceable datasets in terms of the environmental impacts. For the actual data collection on the production tool, again clear guidelines exist in terms of what to measure, mainly through the introduction of the Decider values.

2. The simplicity of the method, which is based on the holistic KPIs and limited data collection, allows the method to be practical and rolled out with less effort that other methodologies. Even if it is applied to entire tool fleets, due to the limited consumables in the focus and only targeting main supply lines, its application is much simpler than previous methods.

3. The accounting of the upstream, downstream and factory impacts means that no impacts can be shifted or overlooked. Additionally, this ensures that even though the upstream impact (prefactory impact) rightfully appears in the calculations and considerations, it can still be separated between consumable supplier and user if necessary. Even though it is used by the user it does not relieve the supplier of their burden nor does it allow the user to ignore it, but rather shows up where optimisation within this footprint could be found.

4. Due to all different dynamic tool behaviours being captured during the measurement period, a much broader range of potential optimisation reductions are seen rather than when applying static, long-term averaged data which is often only percentages attributed to individual tools . Additionally, the dynamic measurement is restricted to main lines, which means the measurement effort is kept at a minimum. Whilst this reduces the measurement effort, solutions for non-intrusive measurement still have to be developed for many applications.

5. Because the method is conducted independent of the product, or the impact different product types have on the overall behaviour are minimal, as shown with the laser, and all consumables as well as their support systems are included in the impact calculations, a holistic approach for the tool and consumables is found. This enables the factory to pinpoint real optimisation potential whilst being able to balance the consumption and impacts and their effects onto each other.

6.3 Future work

For the future, there are different aspects that could be evolved, to give an even more rounded, holistic footprint.

1. The inclusion of KPIs not used in this proof of concept would be the most beneficial. This could be transportation and packaging in the prefactory stage as well as total amount of energy used. Similarly toxicity or eutrophication potential of releases in the posttool stage. Additionally, in the pretool stage, weight of input consumables and efficiency of the support systems could also be introduced with great benefit.

2. A weighting of the KPIs within each stage would also be very beneficial. So that each KPI is normalised on a scale rather than absolute value so that the KPIs are comparable to each other in signifying the value used.

3. The introduction of a standardised optimisation method after the capturing of the dynamic environmental impacts would also benefit the overall application potential of this new method.

Chapter 7 References

[1] U.S. Department of Energy and U. S. E. P. Agency, "Energy Star."
[2] International Organisation for Standardization (ISO), "ISO 14000 essentials."
[3] U.S. Energy Information Administration, "US Energy Nominal Prices," 2011.
[4] Eurostat, "Electricity Prices for Residential Customers," 2011.
[5] Eurostat, "Gas Costs for Residential Customers," 2011.
[6] Eurostat, "Gas Prices for Industrial Consumers " 2011.
[7] Eurostat, "Electricity Prices for Industrial Consumers," 2011.
[8] U.S. Energy Information Administration, "Energy Consumption by Sector http://www.eia.doe.gov/emeu/aer/pdf/pages/sec2.pdf," 2010.
[9] Arbeitsgemeinschaft Energiebilanzen, "Struktur des Energieverbrauchs in Deutschland," 2010.
[10] Sustainable Energy Authority of Ireland, "Fuel Consumption (ktoe) by Sector, Fuel Type and Year http://www.cso.ie/px/sei/Dialog/varval.asp?ma=SEI06&ti=Fuel+Consumption+(ktoe)+by+Sector,+Fuel+Type+and+Year&path=../DATABASE/SEI/Energy Balance Statistics/&lang=1," 2010.
[11] Eurostat, "Number of Enterprises by Sector` http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&language=en&pcode=tin00050&plugin=1," 2011.
[12] Central Statistics Office Ireland, "Motor Vehicles Licensed for the First Time http://www.cso.ie/Quicktables/GetQuickTables.aspx?FileName=TEA01.asp&TableName=Motor+Vehicles+Licensed+for+the+First+Time&StatisticalProduct=DB_TE," 2011.
[13] Central Statistics Office Ireland, "Private households by size 1926 - 2006 http://www.cso.ie/statistics/size_of_households.htm," 2007.
[14] Pacific Northwest Pollution Prevention Resource Center, "Energy and Water Efficiency for Semiconductor Manufacturing," Topical Reports, 1999.
[15] J. B. G. Guinée, M.; et all, , "Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background," Dordrecht: Kluwer Academic Publishers, 2002, p. 692.
[16] T. Ekvall, "Cleaner production tools: LCA and beyond," *Journal of Cleaner Production*, vol. 10, pp. 403-406, 2002.
[17] British Standards Institute, *PAS 2050: Specification for the assessment of the life cycle greenhouse gas emissions of goods and services*, 2008.
[18] British Standards Institute, "Guide to PAS 2050: How to assess the carbon footprint of goods and services," 2008.
[19] Sustainable Energy Ireland (SEI), "Energy Management Systems - Legal Requirements, SEI IS393:2005," S. E. Ireland, Ed., 2005.
[20] Sustainable Energy Ireland (SEI), "Energy Management Systems - Technical Guideline - I.S. 393:2005," 2006.
[21] World Resources Institute, "The Greenhouse Gas Protocol - A Corporate Accounting and Reporting Standard," 2004.
[22] E. Perotto, R. Canziani, R. Marchesi, and P. Butelli, "Environmental performance, indicators and measurement uncertainty in EMS context: a case study," *Journal of Cleaner Production*, vol. 16, pp. 517-530, 2008.
[23] B. G. Hermann, C. Kroeze, and W. Jawjit, "Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and

environmental performance indicators," *Journal of Cleaner Production,* vol. 15, pp. 1787-1796, 2007.

[24] A.-C. Pålsson, "Introduction and guide to LCA data documentation using the CPM data documentation criteria and the SPINE format," Centre for Environmental Assessment of Product and Material Systems (CPM), Chalmers University of Technology, Göteborg 1999.

[25] S. K. Ong, T. H. Koh, and A. Y. C. Nee, "Development of a semi-quantitative pre-LCA tool," *Journal of Materials Processing Technology,* vol. 89-90, pp. 574-582, 1999.

[26] A. Azapagic and R. Clift, "The application of life cycle assessment to process optimisation," *Computers & Chemical Engineering,* vol. 23, pp. 1509-26, 1999.

[27] S. Ahlroth, M. Nilsson, G. Finnveden, O. Hjelm, and E. Hochschorner, "Weighting and valuation in selected environmental systems analysis tools - Suggestions for further developments," *Journal of Cleaner Production,* vol. 19, pp. 145-156, 2011.

[28] A. S. G. Andr, D. R. Andersson, and J. Liu, "Significance of intermediate production processes in life cycle assessment of electronic products assessed using a generic compact model," *Journal of Cleaner Production,* vol. 13, pp. 1269-1279, 2005.

[29] R. Kulkarni, H. C. Zhang, J. Li, and J. Sun, "A framework for environmental impact assessment tools: Comparison validation and application using case study of electronic products," New Orleans, LA, United states, 2005, pp. 210-214.

[30] R. L. Burritt and C. Saka, "Environmental management accounting applications and eco-efficiency: case studies from Japan," *Journal of Cleaner Production,* vol. 14, pp. 1262-1275, 2006.

[31] P. D. Eagan and E. Joeres, "Development of a facility-based environmental performance indicator related to sustainable development," *Journal of Cleaner Production,* vol. 5, pp. 269-278, 1997.

[32] R. Pineda-Henson, A. B. Culaba, and G. A. Mendoza, "Evaluating Environmental Performance of Pulp and Paper Manufacturing Using the Analytic Hierarchy Process and Life-Cycle Assessment," *Journal of Industrial Ecology,* vol. 6, pp. 15-28, 2002.

[33] C. Zopounidis and M. Doumpos, "Multicriteria classification and sorting methods: A literature review," *European Journal of Operational Research,* vol. 138, pp. 229-246, 2002.

[34] V. Benoit and P. Rousseaux, "Aid for aggregating the impacts in Life Cycle assessment," *The International Journal of Life Cycle Assessment,* vol. 8, pp. 74-82, 2003.

[35] B. G. Hermann, C. Kroeze, and W. Jawjit, "Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators," *Journal of Cleaner ProductionNetherlands,* vol. 15, pp. 1787-96, 2007.

[36] C. Jasch, "Environmental performance evaluation and indicators," *Journal of Cleaner Production,* vol. 8, pp. 79-88, 2000.

[37] T. Zobel, C. Almroth, J. Bresky, and J. O. Burman, "Identification and assessment of environmental aspects in an EMS context: An approach to a new reproducible method based on LCA methodology," *Journal of Cleaner Production,* vol. 10, pp. 381-396, 2002.

[38] P. D. Ball, "Modelling Material, Energu and Waste Process Flows to Support Sustainable Manufacturing Activities," in *International Manufacturing Conference (IMC26)* Dublin, Ireland, 2009.
[39] A. A. Burgess and D. J. Brennan, "Application of life cycle assessment to chemical processes," *Chemical Engineering Science*, vol. 56, pp. 2589-2604, 2001.
[40] L. Miller, "Double Counting in Municipal Greenhouse Gas Emissions Inventories," in *17th Annual International Emission Inventory Conference "Inventory Evolution - Portal to Improved Air Quality"*, 2008.
[41] T. O. Wiedmann, M. Lenzen, and J. R. Barrett, "Companies on the scale comparing and benchmarking the sustainability performance of businesses," *Journal of Industrial Ecology*, vol. 13, pp. 361-383, 2009.
[42] Centre for Integrated Sustainability Analysis (University of Sydney), "Dealing with Scope 3."
[43] Andreas Neuber (Applied Materials), "Energy and Cost reduction in semiconductor fabs by applying eco-efficiency engineering," in *SEMICON Europa 2008* Stuttgart, Germany, 2008.
[44] United Nations, *Kyoto Protocol to the United Nations Framework Convention on Climate Change*, 1998.
[45] J. Allwood, "Energy Efficient Low Carbon Manufacturing," in *International Manufacturing Conference* Dublin, 2010.
[46] A. B. Lovins, "Public Lectures in Advanced Energy Efficiency: 2. Industry - at Stanford University," 2007.
[47] U.S. Green Building Council, "Leadership in Energy and Environmental Design http://www.usgbc.org/DisplayPage.aspx?CMSPageID=1988," 2009.
[48] P. Westbrook, "Sustainable Wafer fab - Texas Instruments RFAB," 2007.
[49] C. J. McDonald, "Copy EXACTLY! A paradigm shift in technology transfer method," in *Advanced Semiconductor Manufacturing Conference and Workshop, 1997. IEEE /SEMI*, 1997, pp. 414-417.
[50] W. Tschudi, D. Faulkner, and A. Hebert, "Energy efficiency strategies for cleanrooms without compromising environmental conditions," in *Ashrae Symposium*. vol. 111 PART 2, 2005, pp. 637-645.
[51] Rocky Mountain Institute, "Whole System Design - http://www.rmi.org/rmi/Whole-Systems+Design," 2010.
[52] A. B. Lovins, "Negawatts for Fabs," in *NSF/SRC Environmentally Benign Semiconductor Manufacturing Engineering Research Center's 6 August 1998 Conference*, 1998.
[53] Environmental Protection Agency, "Pollution Prevention Act http://www.epa.gov/p2/pubs/basic.htm."
[54] Environmental Protection Agency, "Design For Environment - http://www.epa.gov/oppt/dfe/pubs/about/index.htm."
[55] T. Masuda, S. Samata, and Y. Mikata, "Virtual fab technology utility simulation and its application to 300 mm CR facility design and energy reduction," in *Semiconductor Manufacturing, 2005. ISSM 2005, IEEE International Symposium on*, 2005, pp. 17-20.
[56] International SEMATECH, "Fab Facility Energy Benchmark Survey," 2003.
[57] European Parliament, "On energy end-use efficiency and energy services and repealing Council Directive 93/76/EE," 2006.
[58] E. D. Williams, R. U. Ayres, and M. Heller, "The 1.7 kilogram microchip: Energy and material use in the production of semiconductor devices," *Environmental Science and Technology*, vol. 36, pp. 5504-5510, 2002.

[59] G. Moore, "Cramming more components onto integrated circuits," *Electronics*, vol. 38, 1965.
[60] W. Den, B. Hsunling, and K. Yuhao, "Organic airborne molecular contamination in semiconductor fabrication clean rooms," *Journal of the Electrochemical Society*, vol. 153, pp. 149-59, 2006.
[61] International Technology Roadmap for Semiconductors (ITRS), www.itrs.net.
[62] R. M. Cohen, "Energy efficiency for semiconductor manufacturing facilities," *ASHRAE Journal*, vol. 45, pp. 28-34, 2003.
[63] I. Dubov, "Chilled water plant efficiency," *ASHRAE Journal*, vol. 45, pp. 37-40, 2003.
[64] I. Dubov, "Heat recovery, energy savings for semiconductor plant," *ASHRAE Journal*, vol. 47, pp. 56-58+60, 2005.
[65] A. Neuber and P. Sethia, "Eco-efficient solutions: reduce energy, costs," *Semiconductor International*, vol. 31, pp. 42-4, 2008.
[66] K. Geoghegan, 2008.
[67] International SEMATECH, A. Giles, and P. Breder, "Analysis of Total Energy Use for Three 300mm Tools," 2008.
[68] S. C. Hu and Y. K. Chuah, "Power consumption of semiconductor fabs in Taiwan," *Energy*, vol. 28, pp. 895-907, 2003.
[69] International Technology Roadmap for Semiconductors (ITRS), "International Technology Roadmap for Semiconductors 2001 Edition Environment, Safety and Health," 2001.
[70] International Technology Roadmap for Semiconductors, "International Technology Roadmap for Semiconductors 2001 Edition Environment, Safety and Health," 2001.
[71] L. Deng and E. Williams, "Measures and trends in energy use of semiconductor manufacturing," in *IEEE International Symposium on Electronics and the Environment*, 2008.
[72] M. C. Williamson, "Energy Efficiency in semiconductor manufacturing: a tool for cost savings and pollution prevention," *Semiconductor Fabtech*, vol. 8, pp. 77-82, 1999.
[73] S. Boyd, D. Dornfeld, and N. Krishnan, "Life cycle inventory of a CMOS chip," in *IEEE International Symposium on Electronics and the Environment* Piscataway, NJ 08855-1331, United States, 2006, pp. 253-257.
[74] F. Taiariol, P. Fea, C. Papuzza, R. Casalino, E. Galbiati, and S. Zappa, "Life cycle assessment of an integrated circuit product," in *IEEE International Symposium on Electronics and the Environment*, 2001, pp. 128-133.
[75] Semiconductor Equipment and Materials International (SEMI), "SEMI S23 - Guide for Conservation of Energy, Utilities and Materials used by Semiconductor Manufacturing Equipment," 2005.
[76] Semiconductor Equipment Association of Japan, "Guidelines for Energy Quantification on Semiconductor Manufacturing Equipment and Utilities SEAJ-E-002E-200301," E. S. Committee, Ed., 2003.
[77] International SEMATECH (ISMI) and Semiconductor Equipment and Materials International (SEMI), "ISMI SEMI S23 TOTAL EQUIVALENT ENERGY (TEE) REPORTING TOOL - http://ismi.sematech.org/modeling/tee.htm."
[78] International SEMATECH (ISMI), "Environment, Safety and Health (ESH) Metrics for Semiconductor Manufacturing Equipment," 2002.
[79] Semiconductor Equipment Association of Japan, "Power Measurement Protocol for Semiconductor Manufacturing Equipment " 2001.

[80] International SEMATECH (ISMI), S. Hinson, R. McKaskle, and T. Huang, "Utility Consumption Characterization Protocol for Semiconductor Tools," 2000.
[81] P. D. Ball, "Modelling Energy Flows across Buildings, Facilities and Manufacturing Operations," in *International Manufacturing Conference (IMC28)* Dublin, Ireland, 2011.
[82] X. S. Ao, J. Matson, P. Kucmas, O. Khrakovsky, X. S. Li, and Panametrics, "Ultrasonic Clamp-On Flow Measurement of Natural Gas, Steam and Compressed Air."
[83] Panametrics, "GC868 Clamp-on Flowmeter http://www.gesensing.com/products/GC868.htm?."
[84] LEM, "LEM AP100-B 10 http://web4.lem.com/docs/products/ap_b10_e.pdf."
[85] Buerkert, "Ultrasonic Flowmeter 8081 http://www.buerkert.com/COM/4421.html."
[86] Omega, "http://www.omega.com/ppt/pptsc.asp?ref=OM-320&ttID=OM-320&Nav=."
[87] The MathWorks, "http://www.mathworks.com/company/events/webinars/wbnr30435.html?id=30435."
[88] E. Chikarakara, S. Naher, and D. Brabazon, "High Speed Laser Surface Modification of Ti-6Al-4V," *Surface and Coatings Technology Journal*, 2011.
[89] D. Moore, S. Krishnamurthy, Y. Chao, Q. Wang, D. Brabazon, and P. J. McNally, "Characteristics of silicon nanocrystals for photovoltaic applications," *physica status solidi (a)*, vol. 208, pp. 604-607.
[90] National Renewable Energy Laboratory USA, 2011.
[91] Canadian Raw Materials Database, 2011.
[92] European Commission - Joint Research Centre, "Life Cycle Tools, Services and Data: http://lca.jrc.ec.europa.eu/lcainfohub/datasetCategories.vm," 2010.

Appendix A – Program that reads in text file and displays original data, on the example of current transducer data

```
% program calling the read in function
% clear
% clc
% tic

set(0,'defaultaxesfontsize',16);
set(0,'defaulttextfontsize',16);

% % -------------------------------------------------------------- %
% % --------------------- Electrical Data ------------------------ %
% % -------------------------------------------------------------- %

voltage_file = fopen('Voltage.txt'); % opening file with current
transducer values in it

% reading in bits from header
Voltage_data = cell2mat(textscan(voltage_file,'%f32 %f32 %f32 %f32'));

fclose(voltage_file);

cab_1 = Voltage_data(:,1)*10; % *10 converts from volt reading to
current equivalent
cab_2 = Voltage_data(:,2)*10;
chill_1 = Voltage_data(:,3)*10;
chill_2 = Voltage_data(:,4)*10;


[num_data bs] = size(cab_1);
num_min = num_data/1000/60;
time_step = num_min/num_data;
time = 0:time_step:num_min;
time = time(1:end-1)';

clear Voltage_data
tic
figure(1)
plot(time, cab_1, 'b'); hold on;
plot(time, cab_2, 'k');
plot(time, chill_1,'c');
plot(time, chill_2, 'g');
axis([0 num_min 0 14]);
ylabel('Current Drawn [A]');
xlabel('Time [min]');
legend('Cab 1', 'Cab 2', 'Chill 1', 'Chill 2');
hold off


toc
```

Appendix B – Program that shortens the data to every 10th value, on the example of current transducer data

```
z = 1;
for i = 6:10:size(cab_1)-5
    % cab_1
    a = cab_1(i-5);
    b = cab_1(i-4);
    c = cab_1(i-3);
    d = cab_1(i-2);
    e = cab_1(i-1);
    f = cab_1(i);
    g = cab_1(i+1);
    h = cab_1(i+2);
    j = cab_1(i+3);
    k = cab_1(i+4);
    cab_1_short(z) = (a+b+c+d+e+f+g+h+j+k)/10;
    % cab_2
    a = cab_2(i-5);
    b = cab_2(i-4);
    c = cab_2(i-3);
    d = cab_2(i-2);
    e = cab_2(i-1);
    f = cab_2(i);
    g = cab_2(i+1);
    h = cab_2(i+2);
    j = cab_2(i+3);
    k = cab_2(i+4);
    cab_2_short(z) = (a+b+c+d+e+f+g+h+j+k)/10;
    % chill_1
    a = chill_1(i-5);
    b = chill_1(i-4);
    c = chill_1(i-3);
    d = chill_1(i-2);
    e = chill_1(i-1);
    f = chill_1(i);
    g = chill_1(i+1);
    h = chill_1(i+2);
    j = chill_1(i+3);
    k = chill_1(i+4);
    chill_1_short(z) = (a+b+c+d+e+f+g+h+j+k)/10;
    % chill_2
    a = chill_2(i-5);
    b = chill_2(i-4);
    c = chill_2(i-3);
    d = chill_2(i-2);
    e = chill_2(i-1);
    f = chill_2(i);
    g = chill_2(i+1);
    h = chill_2(i+2);
    j = chill_2(i+3);
    k = chill_2(i+4);
    chill_2_short(z) = (a+b+c+d+e+f+g+h+j+k)/10;
     % update inside counter(short counter)
    z = z+1;
end
```

Appendix C – Program that determines the volumetric gas flow rate from weight data

```
% program that determines the volumetric flow of gas from the mass
lost at
% any time.

clear
clc
tic

set(0,'defaultaxesfontsize',16);
set(0,'defaulttextfontsize',16);

% reading in the data
[data_in] = textread('Scales.txt','%f');
[datapoints bull] = size(data_in);
data_in = data_in'; % transposing matrix so it is in same form as all
other data created

% creating time indexes and time steps
time_recorded = 110 ; % in minutes
time_steps = time_recorded/datapoints; % gives timesteps between
indexes
[bs datapoints ] = size(data_in);
time_index = time_steps:time_steps:time_recorded;

% % figure(1)
% % plot(time_index, data_in); hold on
% % axis([0 time_recorded 86 96]);
% % xlabel('Time [min]');
% % ylabel('Weight [kg]');
% % legend('Weight reading Scales');

j = 1;
for i = 1: 7: datapoints
    shortie(j) = data_in(i);
    timey(j) = time_index(i);
    j = j+1;
end

%
% figure
% plot(timey, shortie)
% axis([0 time_recorded 86 96]);
% xlabel('Time [min]');
% ylabel('Weight [kg]');
% legend('Weight reading Scales');

[bs datap] = size(shortie);

for i = 1: datap-10

    a = shortie(i);
    b = shortie(i+1);
    c = shortie(i+2);
    d = shortie(i+3);
    e = shortie(i+4);
    f = shortie(i+5);
    g = shortie(i+6);
    h = shortie(i+7);
```

```
    j = shortie(i+8);
    k = shortie(i+9);
    l = shortie(i+10);

    if (a>b) % if there is a drop in the weight ...
        if (b>c)||(b>d) ||(b>e) ||(b>f) ||(b>g) ||(b>h) ||(b>j)
||(b>k) ||(b>l) % ...check if there is a further drop in the next 10
points ...
            flow(i) = 210; %... if there is, its flowing gas
        end
    elseif (a==b) % if there is no drop in the weight...
       if (b>c) ||(b>d) ||(b>e) ||(b>f) ||(b>g) ||(b>h) ||(b>j)
||(b>k) ||(b>l) % check if there is a drop in the next 10 points ...
           flow(i) = 210; %... if there is, its flowing gas
       end
    else
        flow(i) =0; % ... if not then its 0.
    end
end



[bs size_flow] = size(flow);

% find where up and down changes occur, put the indexes into new
variables
for i = 1:size_flow-1
    a = flow(i);
    b = flow(i+1);

    if (a<b)
        markrup(i) = 1;
    elseif (a>b)
        markrdown(i) = 2;
    end
end

% extract actual indexes of changes into shorter variables (i.e.
eliminating
% the 0s
one_ind = find(markrup== 1);
two_ind = find(markrdown == 2);

% defining variable to fill with actual flow values... filled with
zeros,
% so only have to add actual data later on
true_val = zeros(1,size_flow);



[bs size_one] = size(one_ind); % same size as two_ind as what goes up
comes down again

for i = 1: size_one
    %determining the start and end indexes for each rise
    start_i = one_ind(i);
    end_i = two_ind(i);

    % finding the weight value at those indexes
    w_start = shortie(start_i);
    w_end = shortie(end_i);

    % finding the time indexes for those indexes
```

```
    t_start = timey(start_i);
    t_end = timey(end_i);

    % finding the slope between those two points (on original graph)
    grad = abs((w_end - w_start)/(t_end - t_start)); % taking the
absolute value as this is only one required
    grad = (grad/60)*1000; % converting to grams per second

    % finding out the volume consumed using ideal gas equation
    vol = ((grad/39.95)*8.314*293.15)/200000; % in m3/s
    vol_flow_min(i) = vol*1000*60; % in l/min
    vol_flow = vol*1000*60;

    % assigning the flow volume into final variable
    for j = start_i:end_i
        true_val(j) = vol_flow;
    end

end
figure(2)
timmey = timey(1:end-12);
weight_short = shortie(1:end-12);
[AX,H1,H2] = plotyy(timmey,weight_short,timmey,true_val);
xlabel('Time [min]')
set(get(AX(1),'Ylabel'),'String','Weight Drop [kg]')
set(get(AX(2),'Ylabel'),'String','Flowrate [l/min]')
axes(AX(1)); axis([0 time_recorded 87 95])
axes(AX(2)); axis([0 time_recorded 0 40])
set(AX(1),'YTick',[87 89 91 93 95])
set(AX(2),'YTick',[0 10 20 30 40 ])
set(AX(1),'YTickLabel',{'87','89','91','93','95'})
set(AX(2),'YTickLabel',{'0','10','20','30','40'})
```

Appendix D – Purge Gas Flow Calculations on sample data from Experiment C

Timestamp	Weight	Time difference	Weight Difference [kg]	Actual times [s]	Actual time difference [s]	Data points/ second	Gradient [g/second]	Flow [m3/s]	Flow [l/s]	Flow [l/min]
40183 40437	97.33 97.31	254	-0.02	3216.5 3228.38	11.88	21.3805	1.6835	0.0005	0.5135	30.8119
41229 46908	97.31 96.745	5679	-0.565	3297.84 3747.3	449.46	12.6352	1.2571	0.0004	0.3835	23.0071
47990 54389	96.73 96.05	6399	-0.68	3866.51 4439.49	572.98	11.1679	1.1868	0.0004	0.3620	21.7207
55209 62035	96.02 95.305	6826	-0.715	4507.2 5087.02	579.82	11.7726	1.2331	0.0004	0.3762	22.5693
64059 67985	95.28 94.875	3926	-0.405	5273.56 5604.45	330.89	11.8650	1.2240	0.0004	0.3734	22.4014
87769 91933	94.85 94.42	4164	-0.43	7353.22 7719.43	366.21	11.3705	1.1742	0.0004	0.3582	21.4903
92764 96744	94.395 93.98	3980	-0.415	7792.88 8119.39	326.51	12.1895	1.2710	0.0004	0.3877	23.2625
97779 102710	93.96 93.448	4931	-0.512	8223.78 8709.67	485.89	10.1484	1.0537	0.0003	0.3214	19.2857
Explanation		*Difference in Data points*	*Difference in Weight*		*Difference in Seconds*	*Data point Difference/ Difference in seconds*	*Weight Difference*1000/ Difference in Seconds*	*((Gradient/39.95)*8.314*293.15)/200000*	*Flow[m3/s]*1000*	*Flow[l/s]*60*

Appendix E – Plotting all four measurements against the tool action recorded

```
% ---- LOAD shortall2107.mat ---------------------------------------

set(0,'defaultaxesfontsize',16);
set(0,'defaulttextfontsize',16);

num_sec_rec = 7311;% no of seconds recorded

[bs datapoints]= size(cab_1_short);

% creating a time variable
timestep = 0.01;
num_secs = datapoints*timestep;

% ------------------------------------------------------------------
% --- time missing from the measurement.... add here if necessary ---
% ------------------------------------------------------------------
extra_time = 835; % seconds must be determined from data originally!
zeroinfluence = extra_time/timestep; % no of 0s to add to start

% variable storing the zeros to be added in front
peter = zeros(1,zeroinfluence);

% concernating the zeros and actual data
% Power
cab_1_ext = [peter, cab_1_short]*400*sqrt(3);
cab_2_ext = [peter, cab_2_short]*400*sqrt(3);
chill_1_ext = [peter, chill_1_short]*400*sqrt(3);
chill_2_ext = [peter, chill_2_short]*400*sqrt(3);

% Water
pcw_inn_ext = [peter, pcw_inn_short];
pcw_laser_ext = [peter, pcw_laser_short];
pcw_table_ext = [peter, pcw_table_short];

% Temperature
pcw_temp_in_ext = [peter,pcw_t_c_short];
pcw_temp_l_ext = [peter, pcw_t_l_short];
pcw_temp_t_ext = [peter,pcw_t_t_short];

[bs datapoints1]= size(cab_1_ext); % size of new power data

num_secs1 = datapoints1*timestep;
num_min1 = num_secs1/60;

% creating new timevector for this
toyme = 0:timestep:num_secs1;
toyme = toyme(1:end-1); % make index nos matching
toyme2 = toyme(1:end-1);
% ------------------------------------------------------------------
% --- creating variable that shows times when actual recordings where
made from paper ---
% ------------------------------------------------------------------

% uses num_sec_rec as baseline with 0.01 intervals
rec_timeline = 0:num_sec_rec;% time variable in seconds for action
[bs length_time] = size(rec_timeline);
```

```
actionz = zeros(1,length_time); % variable storing action (=1)
% assigning actions to variable (needs to change with every new data
set)
actionz(1452:1514) = 1;
actionz(1655:1672) = 1;
actionz(1779:2308) = 1;
actionz(2333:2342) = 1;
actionz(2438:3023) = 1;
actionz(3084:3293) = 1;
actionz(3423:3445) = 1;
actionz(3574:4239) = 1;
actionz(4304:4916) = 1;
actionz(5501:5503) = 1;
actionz(5652:6240) = 1;
actionz(6260:6849) = 1;
actionz(6885:7207) = 1;

% ---------------------------------------------------------------------
% --- Gas flow data calculated from 1207 weight data.xls
% ---------------------------------------------------------------------

gas_flow = zeros(1,num_sec_rec); % variable storing gasflows (matches
actions)
gas_flow(1452:1514) = 22.14;
gas_flow(1655:1672) = 20.46;
gas_flow(1779:2308) = 26.30;
gas_flow(2333:2342) = 20.34;
gas_flow(2438:3023) = 23.15;
gas_flow(3084:3293) = 26.71;
gas_flow(3423:3445) = 20.8;
gas_flow(3574:4239) = 40.18;
gas_flow(4304:4916) = 22.88;
gas_flow(5501:5503) = 45.76;
gas_flow(5652:6240) = 23.03;
gas_flow(6260:6849) = 23.31;
gas_flow(6885:7207) = 23.30;
gastime = rec_timeline(1:end-1);


% ---------------------------------------------------------------------
% --- Plotting the whole shebang SUBPLOT ---
% ---------------------------------------------------------------------
% plotting electricity
subplot(4,1,1)
plot(rec_timeline, actionz*5000,'r')
hold on
plot(toyme, cab_1_ext,'b')
plot(toyme, cab_2_ext,'k')
plot(toyme, chill_1_ext,'c')
plot(toyme, chill_2_ext,'g')
xlabel ('Time [s]');
ylabel ('Power [VA]');
legend('Action','Laser 1', 'Laser 2','Chiller 1','Chiller 2')
axis([0 num_sec_rec, 0 8000]);
hold off

% plotting water
subplot(4,1,2); hold on
plot(rec_timeline, actionz*50,'k')
plot(toyme, pcw_inn_ext,'b')
plot(toyme, pcw_laser_ext,'r')
plot(toyme, pcw_table_ext,'m')
xlabel ('Time [s]');
```

```
ylabel ('PCW Flow [l/min]');
legend('Action','Flow In','Out Laser','Out Table')
axis([0 num_sec_rec 0 100]);
hold off

% plotting temperature
subplot(4,1,3); hold on
plot(rec_timeline, actionz*20.5,'k')
plot(toyme, pcw_temp_in_ext,'b')
plot(toyme, pcw_temp_l_ext,'r')
plot(toyme, pcw_temp_t_ext,'m')
xlabel ('Time [s]');
ylabel ('Temperature [\circC]');
legend('Action','Temp In','Temp Out Laser','Temp Out Table')
axis([0 num_sec_rec, 18 21]);
hold off

% plotting gas flow
subplot(4,1,4);
plot(gastime, gas_flow); hold on
xlabel ('Time [s]');
ylabel ('Gas Flow [l/min]');
axis([0 num_sec_rec, 0 50]);

figure(2)
plot(toyme, pcw_inn_ext*12,'b'); hold on
plot(gastime, gas_flow*70,'r');
plot(toyme, cab_1_ext*38/1000,'k');
plot(toyme, chill_1_ext*38/1000,'g');
xlabel('Time [s]');
ylabel('Environmental Impact');
legend('PCW In Flow [l/min]','Purge Gas [l/min]','Laser Electricity
[kW]','Chiller Electricity [kW]')
hold off
```

Appendix F – Prefactory Impact Calculation from Excel Data

```
%  Manipulating the output section of the LCI values obtained from the
european LCI databank at
%  http://lca.jrc.ec.europa.eu/lcainfohub/datasetCategories.vm
%  to obtain KPIs such as weight in, waste weight, water & air usage,
GWP
%  potential etc.

% - Copyright Katharina Posten August 2011 - %
clc
clear

% prompt for how many utilities there will be in total
utility_number = input('Enter how many utilities will be read in:');

% loop the entire thing for the amount of utilities
for qqq = 1:utility_number
% ****** Prompting to input which utility is being read in  ******
    utility_name = input('Enter which utility is being read in:',
's');

% 1) Prompting to select the data from the excel sheet by the user
     % select input range for consumable
    fprintf('Select only input values from \n corresponding
consumable. \n Select all 3 columns \n \n')
    [input_values input_names] = xlsread('util_gwp.xls',-1);
    % select output range for consumabl
    fprintf('Select only output values from \n corresponding
consumable.\n  Select all 3 columns \n \n ')
    [output_values output_names] =xlsread('util_gwp.xls',-1);

    % obtaining numbers of inputs, outputs and GWP chemicals
    [ip_ch_lenght bs] = size(input_values); % getting number of inputs
    [op_ch_lenght bs] = size(output_values); % getting number of
outputs

    % variables for collecting total values  --->  KPI's
    % IN
    kg_in =0; % total mass input
    mj_in = 0; % total energy input
    water_in = 0; % total water used in processing
    % OUT
    kg_out = 0; %total waste mass
    waste_heat = 0; % waste heat emitted = wasted energy
    radio = 0; % radioactive amount in output
    co2_eq_out = 0; % total co2 equivalent of all gwp assigned
substances

    % sorting names and descriptions into separate variables for IN
and
    OUT
    % IN
    input_desc = eye(ip_ch_lenght,1); % variable storing middle column
(i.e. value plus measuring unit)
    input_desc = input_names(:,2); % storing the values into this
variable
    input_names = input_names(:,1); % erasing the descriptions from
name variable so now only variable names left in it
```

```
    % OUT
    output_desc = eye(op_ch_lenght,1);  % variable storing middle
column
    output_desc = output_names(:,2); % storing the values into
variable
    output_names = output_names(:,1); % erasing description from name
variable and only keeping variables

    % COLLECTING INPUTS INTO THEIR VARIABLES
    % finding indices of where Mass is and adding those values
together
    (IN)
    for i = 1:ip_ch_lenght
        % looking for MASS match in the chemical description
        m_match = strfind(input_desc(i),'Mass');
        m_match2 = cell2mat(m_match);
        if m_match2 > 1 % adding the values together
            kg_in = kg_in + input_values(i);
        end
    end

    % finding indexes of where water is and adding those together (IN)
    for i = 1:ip_ch_lenght
        % looking for WATER match in input_names
        water_match = strfind(input_names(i), 'water');
        water_match2 = cell2mat(water_match);
        if water_match2 >1
            water_in = water_in + input_values(i);
        end
    end

    % finding indices of where ENERGY is and adding those values
together
    (IN)
    for i = 1:ip_ch_lenght
        % looking for ENERGY match in the chemical description
        e_match = strfind(input_desc(i),'MJ');
        e_match2 = cell2mat(e_match);
        if e_match2 > 1 % adding the values together
            mj_in = mj_in + input_values(i);
        end
    end
    % dividing value by 3.6 to get kWh equivalent
    kwh_in = mj_in/3.6;


    % COLLECTING OUTPUTS INTO THEIR VARIABLES

    % finding indices of where Mass is and adding those values
together
    (OUT)
    for i = 1:op_ch_lenght
        % looking for MASS match in the chemical description
        m_match = strfind(output_desc(i),'Mass');
        m_match2 = cell2mat(m_match);
        if m_match2 > 1 % adding the values together
            kg_out = kg_out + output_values(i);
        end
    end

    % checking wheter first output is in kg
    kg_check = strfind(output_desc(1),'kg');
```

```
    kg_check = cell2mat(kg_check);
    if kg_check > 1
            kg_out = kg_out - 1; % subtracting the 1kg of weight of
the    actual product if it is measured in kg
    end

    % if in m3, it is unchanged and will have to be done manually
    % later on! --> notice check later on!

    % finding indices of where ENERGY is and adding those values
together (OUT)
    for i = 1:op_ch_lenght
        % looking for ENERGY match in the chemical description
        e_match = strfind(output_desc(i),'MJ');
        e_match2 = cell2mat(e_match);
        if e_match2 > 1 % adding the values together
            waste_heat= waste_heat + output_values(i);
        end
    end

    kwh_out = waste_heat/3.6; % Converting Energy output from MJ to
kWh

    % checking wheter first output is in MJ
    mj_check = strfind(output_desc(1),'MJ');
    mj_check = cell2mat(mj_check);
    if mj_check > 1
        waste_heat = waste_heat - 1; % subtracting the 1kWh of energy
of the actual product if it is measured in kWh (originally MJ)
    end

    % finding indices where RADIOACTIVITY is and adding those values
together (OUT)
     for i = 1:op_ch_lenght
        % looking for RADIO match in the chemical description
        e_match = strfind(output_desc(i),'kBq');
        e_match2 = cell2mat(e_match);
        if e_match2 > 1 % adding the values together
            radio = radio + output_values(i);
        end
     end

   %  Reading in Global warming potential data and chemical names
    GWP = [1 25 298 4750 10900 14400 6130 10000 7370 7140 1640 1640
1400 5 146 1810 77 609 725 2310 122 595 14800 675 3500 1430 4470 124
3220 9810 1030 794 1640 22800 17200 7390 1200 8830 10300 7760 9160
9300 7500 17700 14900 6320 756 350 708 659 359 575 580 110 297 59 1870
2800 1500 10300 1 8.7 13];
    GWP = GWP';
    chemical = char('carbon dioxide', 'methane', 'nitrous oxide',
'CFC-11', 'CFC-12', 'CFC-13', 'CFC-113', 'CFC-114', 'CFC-115',
'bromotrifluoromethane', 'bromochlorodifluoromethane',
'dibromotetrafluoromethane', 'carbon tetraclorde', 'methyl bromide',
'methyl chloroform', 'HCFC-22', 'HCFC-123','HCFC-124', 'HCFC-141b',
'HCFC-142b', 'HCFC-225ca', 'HCFC-225cb', 'HFC-23', 'HFC-32', 'HFC-
125', 'HFC-134a', 'HFC-142a', 'HFC-152a','HFC-227ea', 'HFC-236fa',
'HFC-245fa', 'HFC-365mfc', 'HFC-43-10-mee', 'sulfur hexafluoride',
'Nitrogen Trifluoride', 'PFC14', 'PFC116', 'PFC218', 'PFC318', 'PFC3-
1-10', 'PFC4-1-12', 'PFC5-1-14', 'PFC9-1-18', 'Trifluoromethyl sulphur
pentafluoride',  'HFE 125', 'HFE 134', 'HFE 143a', 'HCFE 235da2',
'HFE-245cb2', 'HFE245fa2','HFE254cb2', 'HFE347mcc3', 'HFE347pcf2',
'HFE356pcc3', 'HFE7100', 'HFE7200', 'H-Galden 1040x', 'HG10', 'HG01',
'PFPMIE', 'Dimethylether', 'Methylene chlorine', 'Methylchloride');
```

```
    chemical = cellstr(chemical); %converting character string to cell
format for comparison lateron
    [gwp_lenght bs] = size(GWP); % getting number of GWP

    %  matching kg values with their GWP and getting total GWP value
for all
    %  outputs (includes CO2 values so get TOTAL GWP of outputs) (OUT)
    for i = 1:op_ch_lenght
        op_name = output_names(i);% getting name of to be checked
chemical
        for j = 1:gwp_lenght
            chem = chemical(j);% getting name of first, second, third
... GWP chemical
           % matching chemical name wiht output name, if its a match
add the corresponding output values * its GWP
            comp_gwp_op = strmatch(op_name, chem,'exact');
            if comp_gwp_op > 0 % if values are the same
                gwp_j = GWP(j); % get GWP potential
                chem_mass = output_values(i); % get mass of substance
                gwp_loop = gwp_j*chem_mass; % multiply mass by GWP
                co2_eq_out = co2_eq_out + gwp_loop; % add to total GWP
counter
            end
        end
    end
    co2_eq_out_mmt = co2_eq_out*10^-9; %converting gwp_pot to actual
million metric tonns CO2 equivalence = *10^-9

    % Filling in KPIS
    Waste = kg_in + kg_out - water_in; % calculats waste created.
Already subtracts -1 if its a kg output ... need to include MJ and m3
options
    Energy = kwh_out/kwh_in; % calculates efficiency of system
    Water = water_in; % amount of water used in the process
    Radio = radio; % amount of Radioactivity in the outputs in kBq
    GWP = co2_eq_out_mmt; % Total global warming potential released in
million metric tonns Co2 eqivalence

    EnvImp = Waste + Energy + Water + Radio + GWP; %Gives prefactory
impact for consumables

    conversion_warning = 0;
    % setting marker if output is neither kg or kWh
    odd_check = strfind(output_desc(1),'m3');
    odd_check = cell2mat(odd_check);
    if odd_check >1
        conversion_warning = 1;
    end



     % finding out which line the results will be written in
    if qqq ==1
        irow = 'A2';
    elseif qqq ==2
        irow = 'A3';
    elseif qqq == 3
        irow = 'A4';
    elseif qqq == 4
        irow = 'A5';
    elseif qqq == 5
        irow = 'A5';
    end
    % writing titles into sheet
```

```
    titles_table = {'Consumable', 'Weight IN', 'Energy IN', 'Water
IN', 'Waste Weight', 'Waste Energy', 'Total global warming
potential',' Radioactivity', 'Check unit and convert', 'Prefactory
Impact'};
    xlswrite('Combivalues1.xlsx', titles_table,'Summary Values','A1')
    % writing values into sheet
    values_table = {utility_name, kg_in, kwh_in , water_in, kg_out,
kwh_out, co2_eq_out_mmt, radio, conversion_warning,EnvImp};
    xlswrite('Combivalues1.xlsx',values_table,'Summary Values',irow);

end
```