Metals Required for the UK's Low Carbon Energy System: The case of copper usage in wind farms

Submitted by Ian Keith Falconer to the University of Exeter as a dissertation towards the degree of Master of Science by advanced study in Energy Policy and Sustainability, September 2009.

I certify that all material in the dissertation which is not my own work has been identified with appropriate acknowledgement and referencing and I also certify that no material is included for which a degree has previously been conferred upon me.

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Ian Falconer

Abstract

Using a novel methodology based upon data from publicly available planning documentation, the approximate intensity of copper use is calculated at 5.64 tonnes/MW of wind powered generating capacity installed onshore (based upon data from 30 planned or operating wind farms) and 9.58 tonnes/MW installed offshore (based upon data from 14 planned or operating wind farms).

Analysis of standard decommissioning practice shows that previous estimations of copper availability for recycling may be over-estimated, with 31% of copper used onshore planned to be recycled and 18% offshore. The low copper recovery rates are primarily due to cable decommissioning practices that are justified on the basis of local environmental impact, standard industry practice and technical difficulties in offshore cable recovery.

With technically achievable, but not planned, cable recovery gross recycling rates could rise to 100% onshore and 63% offshore with suitable policy encouragement. A major source of concern is the effective consumption of copper by offshore wind farms, as industry practice is not to attempt recovery of sub-sea grid cables upon decommissioning.

Current copper scrap exports are sufficient to supply all the current and future requirements of the proposed new wind powered generating capacity, but sufficient capacity does not exist to make use of that scrap within the UK.

Table of Contents

Figures

Tables

Supporting CDROM

Contains an electronic copy of this document, working spreadsheets and evidentiary documents.

Definitions

Wind farm – an installation designed to capture energy from wind and convert it to electricity for transmission on an electrical grid

National Grid syn. grid – a pre-existing network of electrical connections that allows the transmission of electrical energy between geographic locations.

Wind turbine or turbine – an element of a wind farm that converts the kinetic energy in wind to electrical energy. Made up of aerodynamic blades, connected to a generator via a hub. The generator is contained in a nacelle, which is held in the wind stream by a tower. The generator is connected to the grid via a transformer, cables and usually a sub-station.

Generator – an element of a wind turbine, usually contained in the nacelle. It converts physical motion into electrical power by inducing current via moving or transient electrical or magnetic fields. Several different designs of generator exist, most contain significant amounts of copper wire.

Transformer – an element of a wind turbine usually contained at the base of the tower or in the nacelle. It converts raw generated electrical current into a form suitable for transmission to a sub-station or straight into the grid. Usually constructed of copper wire wrapped around a soft iron core, transformers often contain a significant proportion of the copper within a wind farm.

Cables – an element of a wind farm or grid connection. Cables are usually constructed of aluminium or copper to meet physical and electrical design criteria. In wind farms these are not simple strands of metal, but highly engineered constructions often built to order. Minimum design specifications exist for cables to help meet safety requirements for the transmission of electricity. These requirements vary with operating temperature, voltage, depth of burial and construction materials so that cables can be safely used in most physical environments.

Life Cycle Analysis (LCA) – a discipline that aims to establish the social, environmental and economic impact of a physical item or activity. Calculations are generally focussed on deriving full life-time total energy balance and/or emissions attributable to that item or activity, however the boundaries can be complex, especially when dealing with recyclable materials and each worker is free to set their own functional limits.

Onshore – constructed wholly on land.

Offshore – constructed wholly on or in the sea or seabed.

Nameplate generating capacity – turbines (and hence wind farms) will have a manufacturer's estimation of maximum safe electrical power output. This may be derived empirically or theoretically and allows an easy comparison between designs. It does not indicate an actual electrical output, as this would depend on local weather conditions, rather it indicates a performance envelope. In most cases this value is given in terms of megawatts (MW). For example; a Vestas V90 turbine can have a nameplate generating capacity of 3MW, showing that under ideal conditions it can safely produce 3MW of electrical power.

Intensity of copper use - by normalising the amount of copper used in each installation to the nameplate generating capacity of that installation we can provide a measure of 'intensity of copper use' that can be used to compare different wind farms. This is given in tonnes of copper used per megawatt of installed capacity

Copper scrap – there is a generally recognised division in copper scrap between 'new' and 'old' scrap. New scrap is clean, without coatings of any kind and generally is made up of off-cuts arising from the manufacturing of items that contain copper, for example trimmings after a transformer has been wound with new copper wire. Old scrap is any other scrap copper that is reclaimed. For example, copper piping previously used in a central heating system would be considered old scrap. Also any scrap with a coating such as wire with insulation is considered ‘old’. The differentiation is mainly on the amount of processing required before it may be added to fresh copper without significantly affecting its physical and electrical properties.

Environmental Impact Assessment (EIA) – a document that is legally required to support most industrial development within the UK or its territorial waters. It is often several hundred pages long, but in the case of large developments can be several thousand pages in length. It contains studies into the way that the proposed development could impact many aspects of the environment in physical, social, economic, cultural, historical and wildlife terms and its submission and acceptance constitutes a major part of the planning process in the UK and most other legislatures.

The contents of each EIA is well defined prior to its commencement and, in the case of UK wind farms, usually includes some resource use assessments in terms of bulk materials and concrete for tower foundations. They do not currently include an explicit assessment of the amount of copper required for the development unless a scoping study identifies it as a key planning constraint, but can often contain information from which it can be inferred for wind farms (See Assumptions and Methodology).

Non-Technical Summary (NTS) - In the UK a Non-Technical Summary of every EIA must be made freely available to the public so that informed consent may be given to a proposed development. This must contain the major findings of the EIA as they impact the planning and consultation process, but its content is otherwise variable. For example; the NTS for a wind farm developed on an old airfield contained no information on access trackways because none were planned to be constructed whereas a wind farm proposed to be built on a peat bog contained extensive detail on all probable ground disturbance.

Environmental Impact Statement (EIS) – on completion of an EIA a definitive EIS may be produced to state what impacts a development will have and whether those impacts are deemed acceptable under planning and environmental law. It will usually constitute a consolidation of the results from an EIA and a set of matrices showing the expected environmental performance of the development.

Introduction

It is generally accepted that renewable energy sources could provide an intrinsically more secure energy source than non-renewable fossil fuels on the basis of long-term availability. This fact has become conflated with the hypothesis that, by shifting to renewable energy sources, global energy systems will naturally become more secure. While there may be some elements of truth buried in this argument, basing arguments for formulating national economic and foreign policy on this premise demands that it be tested.

A shift towards renewable and low carbon power sources is widely accepted to entail a general, cross-sectoral movement towards the supply of electrical power generated by means other than the currently implemented technologies of fossil fuel combustion. In the UK two current government strategies that epitomise the cross-sectoral nature of this economic shift are the development of ultra-low carbon transport[1] and the increased proportion of electricity generated from renewable energy sources, such as wind power, to 15% by 2020[2]. It appears clear from the outset that this shift will probably mean changes in degrees of reliance on specific raw materials, resulting in less absolute reliance on fuels from geological sources or possibly just adding a reliance on an additional set of raw materials, if coal and gas-fired electricity generating capacity with carbon capture and storage is developed. Quite how much of the current reliance on non-renewable fuels will be replaced with reliance on non-renewable metals, if at all, is less clear.

This study will analyse the potential requirements for copper implied by the UK's current policies on wind powered electricity generation. Copper is one of the most widely used metals in electrical systems, irrespective of how the electricity is generated, and its use in those systems is anticipated to continue well into the future. Since copper is almost ubiquitous in electrical systems we can use it to compare high carbon (fossil fuelled electricity generation) and low carbon energy systems (renewable energy powered electricity generation) in terms of their copper consumption or intensity of use in tonnes per megawatt (MW) of nameplate generating capacity, so allowing analysis of potential shifts in resource use patterns for equivalent amounts of generating capacity.

As a first step only, the intensity of copper use in UK wind powered generating capacity will be estimated in this study. Estimations of intensity of copper use in, for example, coal-fired power stations will require significant liaison with equipment manufacturers and power station developers in order to gain access to design detail that is not currently in the public domain, as far as was ascertained during this study. While we can hypothesise that intensity of copper use may be higher in wind powered generating capacity than coal-fired generating capacity, the second half of this equation would require data to support it and time was not available to this study to acquire that data.

However, irrespective of whether copper is more intensely used in renewable generating technologies or non-renewable generating technologies, we can examine what the UK's policy towards the expansion of wind powered generating capacity may mean in terms of national copper consumption and balance of trade in allied metal processing and manufacturing sectors.

This study will briefly address concerns over global copper availability, though it should be stated at the outset that copper is not one of those metals that is of immediate concern in terms of absolute supply constraint by geological availability. 'Peak copper' is not a hypothesis[3] that the study will address directly. However, we will examine the policy priorities that differing stances on resource availability dictate. There are other metals that are of more concern in terms of absolute supply constraint and we would urge interested parties to read the 2008 report on US Critical Minerals Supply[4], available from the National Academies Press, to gain some insight into issues surrounding some of those metals and the sustainability of their use in new technologies.

This researcher is well aware of the second set of supply chain issues with the use of copper, issues that are connected with the global equity and environmental implications of the exploitation of metallic resources. However, it is not within this study's remit to explicitly examine questions regarding long-term sustainability of copper use in the development context or in terms of global environmental impact, though there are interesting avenues for study in those areas.

The global trade in metals is a complex and sensitive international system with a relatively small number of institutions and organisations exerting influence over significant portions of the volume or value of the total material or ownership flow. In the case of copper, and many other metals, geological availability of raw copper ore is also geographically restricted meaning that relatively few countries produce a large proportion of the world's virgin copper metal[5] and the supply chains that provide copper to the areas where it is consumed are focussed on relatively few countries and commercial organisations. That is not to say that new entrants cannot join that supply chain, and indeed they do as every new mine or smelter opens, or every new trader joins an exchange, rather that institutional barriers exist to that entrant becoming a force that would have either a positive or negative impact on supply chain security. Those barriers are mainly financial and, with a sufficiently strong financial backing, dominant positions can be built over time as will be discussed in a later section of this study.

It is currently highly unlikely that a particular metals processor, trader or mine will be able to quickly acquire sufficient market share to exert long-term price control. The world has learnt from past experience that, with a degree of organisation, manipulation of particular commodity prices can happen[6], and as recently as 2005[7] still does, and that this can also have very damaging effects to those markets[8].

The incumbent ad hoc system of using the London Metals Exchange terms and conditions as *de facto* world pricing, delivery and quality standards has its benefits in terms of transparency and continuity[9], though it is not immune from the risk of fraud or manipulation. However, the exchange system is under pressure from long-term bi-lateral contract arrangements favoured by rapidly industrialising and urbanising nations in Asia[10]. Speculation on the role of, especially Chinese, para-statal mining and metals processing companies in dictating large-scale and long-term flows of resources, which are not traded within the open exchange system, is now commonplace within business[11], NGO[12] and academic[13] sectors. Many commentators see, at the very least, opportunistic actions by China to acquire access to mineral resources[14] and some hypothesise about manipulation[15] within the rapidly evolving metals markets. The *volume* of the physical refined copper trade carried out through exchanges and the volume of direct trades is roughly equal[16], with the trade in futures and more arcane contract derivatives confined to the exchange markets. The *value* of the copper trade is therefore concentrated in the exchanges for reasons that we will discuss in later analysis.

This study will look at the copper trade in terms of where the UK may be able get the copper that it needs, and under what constraint that supply is likely to come, since any major shifts regarding copper supplies may require policy-level responses to ensure that its supply chain is a secure base upon which to found the UK's new energy system.

Finally this study will consider, qualitatively, the potential effects of current policy in securing the copper supply chain for future generations within the UK.

We will leave the reader with the question at the heart of this study: if it is shown that the UK is placing reliance on a metal, the supply of which is just as subject to individual and institutional speculation, manipulation and supply constraint as current oil and gas supplies, does it then follow that using more of that metal per unit of electricity generating capacity will make the country's energy supply more secure ?

Assumptions

Without full access to comprehensive copper consumption data, broken down on a per technology basis, some assumptions must be made and justified. These are detailed below.

Data Sources

Data on the specific copper requirements in wind farm construction is fragmentary. There appears to be a marked difference in approach to data disclosure between onshore and offshore wind farms, even between wind farms developed by the same company. This is a function of scale with current onshore wind farms only subject to gaining consent under Section 36 of The Electricity Act 1989[17] if their generating capacity is over 50MW (this applied to 8 out of the 47 of the developments in this study), while offshore wind farms in UK territorial waters over 1MW are subject to gaining consent under the same act[18].

We have only included raw data from wind farm developers that has been submitted to the planning process or under the requirements of The Electricity Act, except in the case of offshore wind farms where a portion of the design detail was taken from a detailed report compiled by The University of Groningen, Deutsche WindGuard GmbH and the German Energy Agency (DENA) for the State of Bremmen[19] which related to offshore wind farms in European waters. This data was excluded from full analysis in order to retain methodological consistency between the two types of wind farm. One proposed offshore wind farm in Eire (Codling Bank) was included in full analysis as its documentation was sufficiently close to UK EIA requirements as to make it functionally identical.

Additional meta-data is available from the various industry groups (EWEA, BWEA, Copper.org, etc), but we have taken the view that only data that can be directly attributed to wind farm developers should be considered authoritative where it concerns their proposed or actual developments.

Installed vs. Planned

We have assumed that the data seen in EIAs, their Non-Technical Summaries, associated public consultations, and other various sources is representative of actual installations, whether planned or already in place. We have taken the view that, to a very large extent, the distinction between planned and installed is irrelevant for the purposes of this study since the technology employed does not substantially change.

Modifications to wind farm designs as they progress through the planning process do not, on the whole, greatly impact the design criteria that affect minimum copper use on per MW basis. For example; changes to maximum blade tip height made in response to concerns about visual amenity may limit the efficiency of a wind farm but not its copper use, the total number of turbines in a wind farm may affect total copper used but not intensity of its use, and changing the exact location of specific turbines may impact cable routing but it will usually increase it from a theoretical minimum. Siting tolerances (the micro-variation of turbine foundation site due to local conditions found during construction) are considered to have negligible effect on net cable run lengths.

If a fully quantitative analysis of copper usage were to be carried out it could only be approached for completed installations, and we would suggest that analysis of purchasing and shipping records could provide the bulk of the data necessary to complete such a study. We have taken the view that this study is semi-quantitative, with an aim to provide an ‘order of magnitude’ for copper use in wind farms that is useful at a policy level, highlights data gaps and can be used to provide direction for future quantitative studies.

Detailed Electrical Design and Engineering

For the reasons stated above we have, wherever possible, ignored electrical design details. Systems such as reactive power compensation, lightning protection and generator design may influence the intensity of copper use in wind powered generating systems. However, analysis that includes those details is best left to a skilled engineer with more time and access to real-world electrical designs than was available to this study.

Turbine Design

We have assumed that all turbines in this study conform to the current industry norms as shown in Figure 1, below. Rotating blades are connected via a longitudinal shaft and gearbox to an electrical generator. The generator is electrically connected via a transformer, usually placed at the base of each tower, to 33kV cabling that runs to a sub-station and/or switch-gear that is able to export electrical power through a connection to the National Grid.

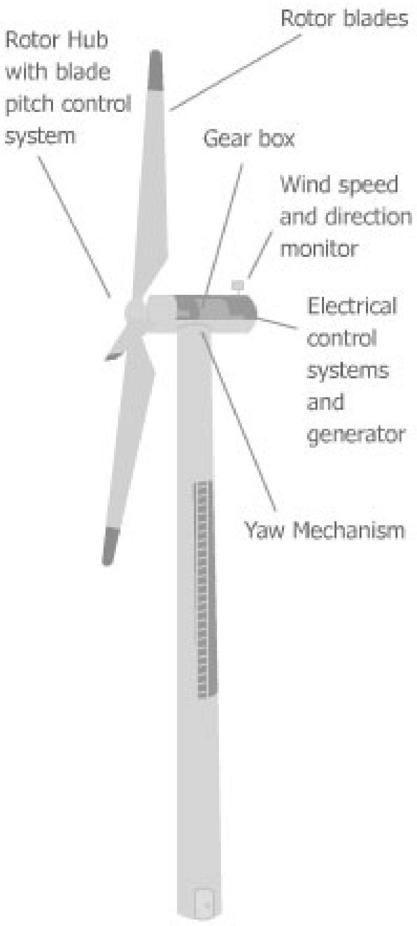

Figure 1: Typical 3-blade, horizontal axis, upwind, wind turbine design. Source BWEA

Access Track Length Equals Cable Route Length for Onshore Farms

The main cause of ground disturbance in onshore wind farms is considered to be the construction of tower foundations and access tracks. In the UK it appears standard practice to make the access tracks semi-permanent i.e. to last the lifetime of the wind farm planning permission, and to co-locate cable routing alongside them[20]. Access tracks can therefore act as a good proxy for cable lengths between turbines, switch gear and grid connection.

This single piece of engineering standard practice makes it relatively easy to establish the approximate length of cable trenching, and hence cables, even where it is not stated, since showing the length of the access tracks is a requirement within most EIAs. In the majority of cases some demonstration of access track length is made within the non-technical summary (NTS) of the EIA rendering procurement of the full technical detail unnecessary for a policy-level analysis.

This has a significant cost and time benefit to the researcher because, while EIAs are public documents, they are kept in planning departments in paper form and are not generally available online. Copies on CD-ROM can be requested from either the developer or the appropriate planning office, but this comes with a cost implication as both will charge a distribution fee to cover their own costs. This fee is usually between £5 and £30 per assessment distributed on CD-ROM. The NTSs are freely available online in the majority of cases and many NTSs, other than those included in this study, remain to be analysed. It should be noted however that once planning consent has been given there is no obligation on the developer's part to continue to make NTSs available making this data source transitory.

The corollary to the use of the trackway-cable equivalence is that on some brown-field sites, notably disused airfields, no new access tracks are required and no definitive cable trench length is given in either the NTS or full EIA document making it impossible to reach an estimation of cable length. These wind farms constituted a small minority of those analysed and have been excluded from the data set. They are, by their own nature, limited in aerial extent and so contain relatively few turbines.

However, it was also found that access track length alone does not give an accurate assessment of total copper requirement since the cable conductor diameter may vary between wind farms and even between unconnected turbines within the same wind farm. The detail of this variation is contained within commercially sensitive design detail that is not required for submission in support of a planning application. In order to reach a more reliable estimation of the copper requirements within wind farm cabling some further assumptions must be made and justified.

Turbine Output

For the purposes of this study we have assumed that all turbine transformers are providing 3-phase Alternating Current (AC) and are suitable to be connected to an uncompensated 33kV AC circuit that is directly connected, possibly via other turbine's transformers, to a sub-station where the current output for the whole wind farm is conditioned before it reaches the National Grid.

We realize that this represents a gross simplification of the detailed electrical design, but analysis of current surges and harmonics are not necessary in order to reach an 'order of magnitude' estimation of the total minimum copper requirements of modern wind farms.

Internal Cable Designs

For the purposes of this study we will assume that all cabling for onshore wind farms is placed underground to the point of grid connection that is co-located with the farm's sub-station. This is a reasonable assumption for small to mid-sized installations that have a grid connection at or below 132kV, the vast majority of which connect to the grid at 33kV. We will term this cabling as ‘internal’ to the wind farm. We have seen the term ‘inter-turbine cabling’ used in some documents but consider it too proscriptive since not all cabling on a wind farm is just between turbines, but should also include the sub-station.

Internal cabling between modern wind turbines and their sub-stations appears to use 33kV 3-phase AC transmission as a standard in the UK (sometimes 36kV within the EU), with the export voltage dependent on the availability of a suitable connection point on the National Grid. In most rural locations in the UK the nearest available point for grid connection will be at or below a voltage of 132kV. However, some large onshore wind farms and several offshore wind farms required to connect to the grid at voltages above 132kV for technical and regulatory reasons. Since the grid connection voltage level is not the same for all wind farms and the National Grid has fixed location, the cabling between the sub-station and the nearest available grid connection has not been included in this analysis. It is also the case that onshore grid links may be overhead power lines and may not be made of copper. A rigorous quantitative analysis should assess the contribution to total copper consumption of this link.

In this study underground/undersea cabling capable of operating at voltages of 220kV or less was found to be constructed using copper conductor surrounded by various insulating, shielding and armouring layers. The use of copper appears to be justified on the basis of its superior corrosion resistance over the alternative aluminium conductors, and because weight is not an issue. We have used ‘off-the-shelf’ Nexans 19/33 (36) kV 3-core copper XLPE (Cross-Linked Polyethylene) cable as our reference cable for all voltages at or below 36kV as it was the only cable specified of any brand, in any EIA that we found, and it appears to have typical performance for the current capacity.

Larger wind farms and those offshore may use custom designed cabling that includes communications links in the form of optical fibre or copper cable capable of carrying signals to and from monitoring and control equipment in each turbine. Smaller wind farms may simply run a second off-the-shelf communications cable to satisfy the same requirements. We have not included communications cables in this study as their diameter is very small compared with power cables.

Offshore Cable Designs

Larger wind farms may be obliged by regulation or economically justify connection into higher voltage portions of the grid, but this will often require that additional overhead power lines be installed and as previously stated we have chosen to exclude that link in the wind farm chain from our analysis.

For offshore wind farms the situation is slightly different. We have retained the term ‘internal’ to include all cabling between turbines and their sub-station, however the wind farm to onshore grid inter-connector will be considered separately. Since there is currently no offshore grid to connect into, the wind farm to onshore grid inter-connector must be considered an essential part of the design in the same manner as the internal cabling. We also feel that the inter-connector is an essential source of data on the whole system copper usage since it will be of a diameter large enough to safely conduct the combined power output of the entire wind farm.

Again copper appears to be the conductor of choice offshore and we will assume that all cabling has a copper core up to the point of connection with the onshore grid. We feel this is a reasonable assumption since the designs that we have seen all feature an underground landfall and underground cable routing to an onshore sub-station, and that the corrosion resistance of copper cabling represents a design advantage for installations with a 25-50 year tenure obtained from the Crown Estate[21].

In our literature search, few companies were able to supply off-the-shelf cable with capacity to support voltages of 132kV or above. We have used single core, lead sheath high voltage cables from Taihan Electric Wire Company of South Korea as our reference cable design for voltages over 36kV. However, since current capacity was not supplied we have used the Nexans 33kV XLPE performance envelope and extended it into the Taihan design range. These high performance cable designs vary in flexibility, resistance to corrosion and physical damage and heat dissipation properties, but not in the standard of copper used. Since there is no physical difference in the copper conductor itself, we feel that it is reasonable to extend our cable diameter model using the Nexans 19/33kV current carrying capacities.

In order to 'correct' for use in a 3-phase system the current capacity of individual conductors has been multiplied by $3\sqrt{3}$, so that a total copper requirement per metre may be calculated.

In Europe the assumption that copper is the conductor of choice from wind farm to grid is not necessarily as strong as it is in the UK since there appears to be a design preference for aluminium conductors to be used once the cable has reached landfall.

However, no offshore wind farms located outside the UK were included in the full intensity of cooper use analysis so we feel that these assumptions provide a reasonable framework.

Cable Specifications

In undertaking this study we have found a marked reluctance on the parts of onshore wind farm developers in the UK to release details on the type and amount of cabling used. Data requests were sent to all major UK wind farm developers with no positive outcomes. To some extent we can understand this attitude as the installation of cables with a higher specification than currently required by electrical safety standards would represent a speculative investment in developing a property and could be seen by some as an assumption that planning permission would be given for an upgrade in the future.

However, cabling standards exist for these installations and obfuscation of this particular data serves no real purpose, since every wind farm developer of note will have access to the same set of design criteria and regional wind data. Indeed it could be argued that over-specification of underground cabling represents an upgrade of the property itself as it is ‘turbine upgrade ready’ and, if it could be placed on the company’s books as such, could attract a higher resale valuation. In a world of variable copper prices this could represent a valuable hedge against raw material price rises. Apparently the data is not seen in those terms within the industry.

For the purposes of this study we have assumed that a minimum cable specification for modern wind farm developments is used whereby the conductor diameter is the minimum required to safely supply the maximum power output of the wind farm. We have assumed all turbines will output at a nominal 690V, which will be stepped up to 33kV 3-phase AC for transmission to the wind farm sub-station. The diameter of the conductor used will vary according to nameplate generating capacity of the turbine and the number of turbines connected to the sub-station via each cable.

Data on offshore cabling is slightly less restricted and publicly accessible information usually includes at least some discussion of internal cabling and the wind farm to shore inter-connector design.

Where no discussion of internal cabling is published the turbine spacing can be used as a direct proxy for cable lengths, since the vast majority of cable runs will be straight lines and minimum distance. The error due to cable J-risers bringing seabed cable up to the turbine transformer is variable with sea depth on a turbine-by-turbine basis, so has been excluded from this study. Typical sea depths seen in the current generation of offshore wind farms are less than 30m, so compared with the average inter-turbine cable run found by this study of 650m, this represents less than a 4.6% systematic error. We consider this negligible in the context of this study. It is possible, where transformers are mounted in the nacelle, that this error could rise considerably with the seabed to nacelle distance adding another 15% to that systematic error. Clearly a 20% systematic error is appreciable, however without access to detailed real-world specifications we have decided not to account for sea-depth and tower height.

Where grid connection for onshore wind farms is often covered by a separate planning consent in the UK, the wind farm to shore inter-connector is generally considered under the wind farm planning consent until the cable reaches landfall, where it will again usually become subject to a separate planning consent. Where possible we have added both onshore and offshore sections of inter-connectors as this could constitute a substantial copper use. For example; one planned offshore wind farm found by this study has proposed a 40km cable run onshore to reach a suitable grid connection point, and cable runs of 5km are not unusual from landfall to grid connection point.

The design of each inter-connector is project specific and we can make few assumptions in this rapidly evolving field of wind farm design. ‘Early’ offshore wind farms, such as Scroby Sands, have multiple inter-connectors that are simply extensions of the internal cabling using 3-phase AC at 33kV, whilst the latest designs use High Voltage Direct Current at 132kV or higher.

For the purposes of this study we have excluded the one offshore wind farm design where HVDC was specified, since it represents a different technology and its intensity of copper use may reasonably be assumed to be different.

Cabling Layout

Onshore wind farm layout is defined by both physical and social factors, so generalizations about optimal layout of both turbines and cabling are next to irrelevant especially where a planning decision can be made on criteria as variable as visual amenity.

Empirical assessments of track-side cable runs provide a relatively robust data set for reasons discussed above, however the number of cables and their topology is a design detail that can be subject to company engineering policy or an individual engineers design ethic as much as it is subject to minimum safety requirements. For example inspection of Scottish Power’s approved cables list shows no 3-core copper cable rated at 33kV pre-approved for general use. That is not to say that a specific wind farm installation could never use a 3-core copper conductor, but that it must be approved for specific use within that company’s internal design process.

Different cable topologies can and do exist, each providing differing balances between redundancy, performance and cost. Larger wind farms may opt for more redundancy, achieved through replication of equipment or more inter-connected internal cable layouts, in order that operation may be more continuous. Smaller wind farms may be optimised for lower capital cost in order to provide a quicker financial return. However, these design options are installation specific and it is difficult to provide a reasonable general model on limited data without over complicating matters.

For this study we have used a least distance, 33kV single 3-core cable as the standard and used a least diameter approximation to estimate which of the standard conductor diameters available would be most appropriate. We recognize that this may represent an under-estimation of total cable requirements especially where wind farms are designed on a turbine cluster basis, or an over-estimation where the wind farm has a small number of turbines, however without access to a range of detailed designs, process control documentation or engineers we must come to a reasonable generalization in full knowledge of its deficiencies.

Copper Contained in the Turbine and its Components

A small number of detailed life cycle assessments (LCA) of wind farms exist. In the absence of manufacturer raw material breakdowns (also apparently considered commercially sensitive), these are assumed to provide the best available data on total copper contained in wind farm components. All LCA data contained in this study is provided via peer-reviewed journals, however at least one major deficiency was seen in all the LCAs. This discrepancy does not affect the findings of this study, but should be of interest to those carrying out LCAs on wind farms in the UK in the future and is discussed below.

A simple average of the small number of available data points was used to derive a model for copper use within the turbines themselves. This has provided a single value that has been applied to all turbines that, while it appears a reasonable figure in itself, is not robust and would provide a first point of call to further validate this portion of the dataset.

Only one LCA was located that contained life cycle data on offshore wind farm grid inter-connectors (Schleisner, 2000). That paper was found after data analysis was started and contained sufficiently parallel data to act as control for this study, so was not included in the data. However it will be referenced in the analysis.

Methodology

Publicly accessible data was used throughout this study, and while data was sought from several wind farm developers and turbine manufacturers, none were willing to allow access to their detailed designs for use in this study.

Electronic copies of all documents that provided raw data are included on the attached CD-ROM, as are working spreadsheets used to collate and analyse that data. These spreadsheets are left unsecured to allow full inspection of the equations and transforms used.

Metric units are used throughout unless stated. The US dollar is used as the currency of most relevance to the copper trade, though UK trade balances will remain in pounds sterling unless stated. An exchange rate of \$1.75 to £1.00 was used where conversions were necessary.

General

A key piece of evidence was derived from three peer-reviewed papers (Ardente et al (2006), Crawford (2009), Martinez (2009)). This related to the amount of copper used within wind turbine components and forms the basis for some estimations used in this study.

As previously discussed these data are considered a key weakness because, though the papers are internally consistent, none of the authors were aiming to provide data in a form that was easily usable in this study and each had their own methodology.

If this study were to be repeated wind turbine component manufacturers should be approached to provide a resource use breakdown for their standard turbine models, in order to provide additional reassurance that the figures used in this study are valid. At present we believe that they represent an appropriate order of magnitude value for copper use, but would prefer a more robust data point upon which to build a study of this scale.

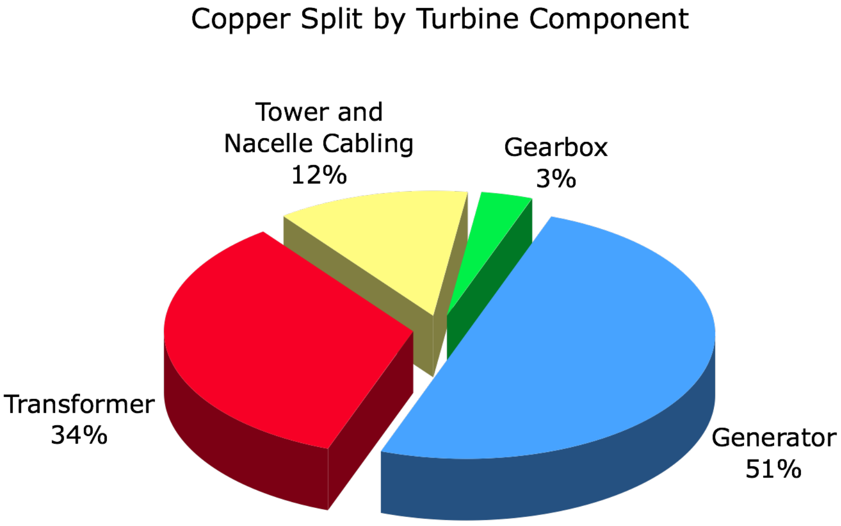

Figure 2: Showing the proportion of copper contained within the elements of a wind turbine. Source – Ardente at al (2006), Crawford (2009), Martinez et al (2009)

The copper use breakdown used is as follows:

Generator	0.360 tonnes/MW
Transformer	1.000 tonnes/MW
Cabling within the turbine and tower	0.306 tonnes/MW
Gearbox	0.079 tonnes/MW

Onshore

A web search using the terms “wind farm”, “Non-technical summary” and “Environmental Impact Assessment” was made using several search engines and the documents returned were inspected to verify their applicability.

This selection was made on the basis of source (apart from peer-reviewed journals, only raw data originating from wind farm developers, planning authorities and government sources were included in this study) and content (only documents that were clearly attributable to a wind farm that was in advanced planning, construction or operation stages were considered). We considered plans that included a map drawn to scale or showed relevant design detail as being sufficiently advanced to be included. Maps of turbine layouts were measured where a scale was included and, as discussed, access track-ways used as a proxy for cable runs.

The majority of the data came from the Non-Technical Summaries (NTS) of full EIAs. Most of these documents included a map showing road and turbine layouts, discussed the amount of new and upgraded access trackways required or, in rare cases, the amount of cable to be run. Since only two sources discussed the actual length of cable used in their wind farm construction, and did so without reference to the type, diameter or intended use of that cable, these data have been excluded from this study as they potentially included communications cables. The length of communications cables is assumed to be roughly equal to that of power cables. However, in the cases where copper is used instead of optical fibre, their smaller diameter makes their copper consumption very small compared with power cables.

A total of 47 onshore wind farms were analysed with 30 of those installations providing sufficient data for full analysis. The remaining 17 (totalling 282 turbines) provided data that was included in partial analysis. A total of 648 turbines were fully included in this study, constituting 1,814.9 MW of nameplate generating capacity. Data was discarded on the basis of not providing access trackway length either through map or in text.

Offshore

In addition to using the NTSs of several UK installations, we initially included wind farms in Europe on the basis that their design and implementation was inherently international and that the local planning process would have less impact on design optimisation in the offshore situation. In other words we assumed that a more uniform set of design features should exist in offshore wind farms that are not dependent on the territorial waters in which the wind farm is built, but where minimum electrical safety requirements are broadly similar.

Gerdes et al (2006)[22] provided the balance of the data. Many of the raw data taken from Gerdes were corroborated using other sources, for example an NTS or wind farm developer publicity material, or Breton & Moe (2009)[23]. However in final analysis only offshore wind farms in the UK were included in order to retain methodological consistency with the onshore section of this study and we found that this made no material difference to the findings.

A total of 31 offshore wind farms were analysed with 14 being found to provide sufficient data to be fully included in this study. Of the remaining 17, 10 did not provide sufficient data to support analysis and 6 were excluded on the basis that they were located outside UK waters. One proposed wind farm was excluded on the basis that its developers planned to use a HVDC inter-connector rather than the HVAC inter-connectors seen in all other cases. A total of 1810 turbines were included in this portion of the study, constituting 5,869.4 MW of nameplate generating capacity. Data was discarded on the basis of providing no detail on turbine spacing (which in turn can be used as a proxy for minimum cable run lengths) or providing insufficient detail on the wind farm to shore interconnector.

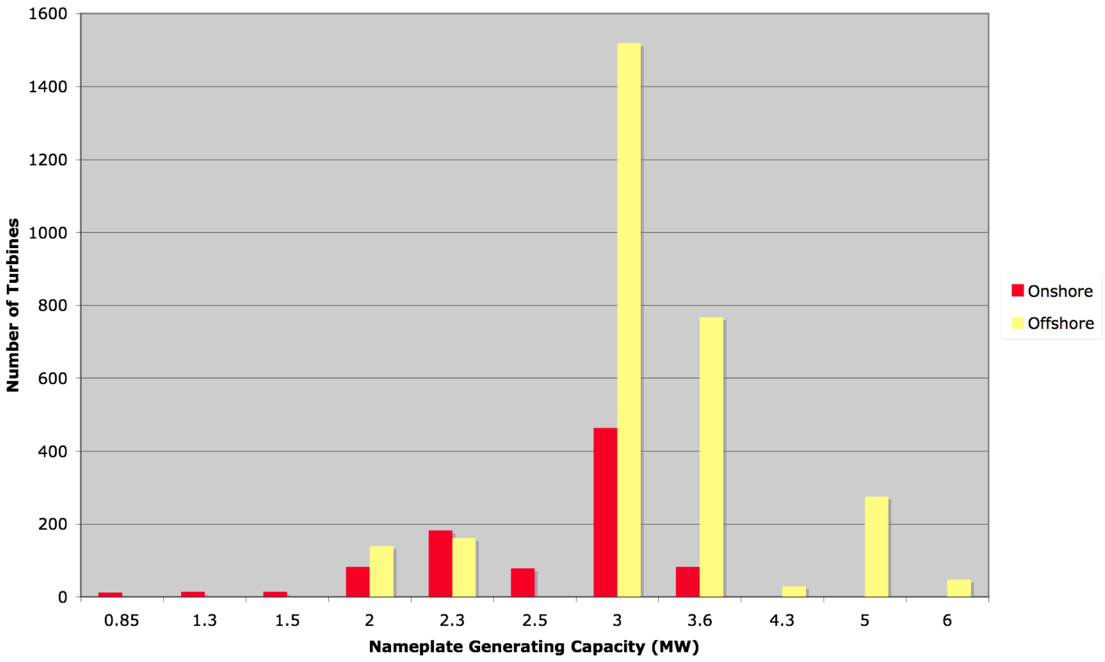

Figure 3: Histogram showing numbers of turbines installed or planned by their nameplate generating capacity in onshore wind farms (red) and offshore wind farms (yellow). Source - Various

Few of the wind farm NTS documents included explicit design detail on the inter-connectors, though several made reference to numbers of cables, their proposed length and voltage capacity. However, several of the wind farms require accompanying onshore installations and onshore cable routes to an appropriate grid connection point. The documents supporting planning permission applications for these installations provided useful additional detail and we have included cable requirements past landfall where possible.

Cabling Capacity Matrices

In order to provide a reasonable assessment of cabling requirements, a set of matrices of cable specifications was constructed (see Appendices One, Two and Three) that includes an estimation of the maximum number of turbines of a specific nameplate generating capacity that can be connected via a each cable.

Each matrix was constructed using the simple formula; Power = Current x Voltage and the relationship between copper conductor cross-sectional area and its current carrying capacity to provide the mass of copper used per meter of cabling required by different configurations of turbine capacity and number. The matrices were referenced during estimation of the internal and inter-connector cabling requirements for each wind farm.

We would assume that better tools exist to aid the electrical engineer in the process of wind farm design and cable selection. However, such as tool was not found and the simple matrix concept is adequate for this study's semi-quantitative approach.

Findings and Critique of Data

Life Cycle Assessments

In the LCAs inspected there was an assumption of metals recycling rates for wind turbines, commonly stated at between 80% and 95%, but initially only one analysis of an entire wind farm was found that included the supporting infrastructure[24]. It was unclear what was being measured in terms of cabling in that study. So while its assessment of copper contained in the turbine itself was used, data from Ardente (2006) on cabling was not. Table 1 summarises the data used.

Total Copper Used	**Generator (t)**	**Transformer (t)**	**Cabling (t)**	**Gearbox (t)**
Ardente, 2006	0.924			
Marinez, 2009	2	1.5		
Crawford, 2009	0.37	0.357	0.24	0.062
	1.43	1.38	0.94	0.241
Average /MW	0.360	1.000	0.306	0.079

Table 1: Showing a summary of the findings from LCA studies carried out on wind turbines as they pertain to copper usage. Sources as shown.

Schleisner (2000)[25] has been used as a 'control' and is excluded at this point as discussed below. Weinzettel et al (2009) [26] was excluded on the basis that it represents a fundamentally different technological path and is also discussed below.

Inspection of UK wind farm decommissioning schedules shows that in only one case, out of 47 onshore wind farms studied, was recovery of buried cables anticipated upon decommissioning. So, while the data found in existing LCA assessments of wind farms may indeed be valid for the towers, nacelles, blades and other components we do not believe that the recycling rates are valid for the cabling infrastructure. This could have a significant impact on certain aspects of wind farm LCAs and their conclusions regarding life-cycle impacts of the installations in terms of energy consumption and environmental emissions during manufacture, and especially the payback times.

Martinez et al (2009)[27] assume a 95% recovery rate for copper contained in wind turbines and state that the metal has ‘enormous value and environmental impact’. Crawford (2009)[28] calculates copper’s embodied energy at 379 GJ/tonne, the highest of all the major ‘raw’ materials contained in wind turbines, and compared to steel at 85 GJ/tonne. So the importance of copper as a constituent of wind turbines is being recognised and analysed, but some crucial real-world data on implementation is not.

A meta-analysis by Lenzen et al (2000)[29] showed that small-scale (95kW) wind turbines in Denmark could approach 80% recycled scrap copper content, though did not differentiate between new scrap (essentially made up of off-cuts during component manufacturing) and old scrap that was previously contained in an actual product that was used.

This is a crucial differentiation that has impacts both in terms of required energy to manufacture and transport turbine components and in total copper material flows across national boundaries. The British Geological Survey (2004) estimates that of the roughly 42% of copper scrap which is recycled in the UK, 37% is new scrap and 5% is old scrap[30].

It is not known what proportion of copper is recovered from mixed electrical waste collected under the European WEEE Directive and, mostly, exported. However, industrial componentry such as that found in large wind turbines may have a second use, after reconditioning, before recycling or it may be stripped and selectively recycled. We have found no data on the specifics of this process for wind turbines or their supporting infrastructure, but we suspect that the amount of copper recycled from components of wind turbines will be higher than current UK averages.

While we have great respect for the methodological rigour in the LCA approach, some studies seem to fall short in real-world applicability as they define their ‘world’ in terms of componentry rather than function. This limits the use of their data outside their intended, specialist audience. For example, a 2MW wind turbine is unlikely to be used off-grid, but most LCAs do not consider the grid connection as part of the functional installation. We would urge exponents of the LCA approach to include the infrastructure essential to electrical production and export to grid in future studies of large wind power systems.

The Exceptions

Schleisner (2000)[31] carried out an LCA on two wind farms in Denmark. One consisted of 10 x 500kW turbines and their grid inter-connector. The other consisted of 18 x 500kW turbines onshore. This paper was located late in the process of compiling this study but provided invaluable corroboration for, in particular, its findings on offshore grid inter-connectors.

It was felt that Schleisner’s findings would be more valuable as a point of reference rather than being included as a way to increase the robustness of the dataset as described above, with the proviso that the turbines in her dataset had an individual capacity of 0.5

MW whereas the minimum in this study's dataset was 0.85 MW and averaged 3.4 MW offshore.

Copper use	**Onshore Total (t)**	**Onshore /MW**	**Offshore Total (t)**	**Offshore /MW**
In turbines	6.3	0.7	3.5	0.7
In 'sea cables'	0		25.8	5.16

Table 2: Showing a summary of Schleisner's results as they pertain to copper use in Danish wind farms.

The inclusion of Schleisner's data would decrease average copper usage of the turbines in this study from 1.745 tonnes/MW to 1.223 tonnes/MW or by roughly 30%. In the context of a semi-quantitative and order of magnitude study this is not considered a major deficiency, especially when the turbines involved were significantly older and smaller than most of those included in this study.

The variance between Schleisner's data on the offshore 'sea cables' (5.16 tonnes/MW) and this study's model (7.84 tonnes/MW) was also approximately 34%. In a dataset of two points, this shows a good degree of agreement.

The use of Schleisner's dataset as a control serves to highlight the need for more quantitative life cycle data on wind farms and their cabling, but also corroborated our findings and provided a degree of validation to our methodology. The relatively low copper consumption in Schleisner's onshore wind farm dataset may reflect several different factors and its location in Denmark, where planning controls and physical location may work together to optimise cable run length, cannot be discounted.

Weinzettel et al (2009) [32] show that, for a floating wind turbine spar-type concept, total copper usage reached 58.5 tonnes per 5MW turbine or 11.7 tonnes/MW, but make no separation between the elements of the system. That assessment is on the basis of 40 turbines at 50km from shore. Since this represents a fundamentally different design we include this data to serve as a qualitative illustration of the possible rising intensity of copper use as wind energy systems venture further offshore.

Total Copper Usage in Wind Farms

Onshore Wind Farms

The data collected shows that, on average, UK wind farms require 5.64 tonnes of copper per MW of nameplate generating capacity installed, or a total of 15.78 tonnes per turbine. Of that amount copper 4.89 tonnes is contained in the turbine and its transformer and 10.9 tonnes is contained in the cabling between the turbine and the sub-station.

Offshore Wind Farms

The data shows that on average offshore wind farms require 31.07 tonnes of copper per turbine installed or 9.58 tonnes/MW. Of that copper, 1.75 tonnes is contained in the turbine and its transformer and 6.05 tonnes is contained in the cabling between the turbine and the sub-station. It follows that on an isolated basis, wind farms require 19.63 tonnes per turbine installed or 6.05 tonnes/MW installed but not connected to the grid.

Since both onshore and offshore data is modelled on the same wind turbine LCAs shown above and used the same cable specifications, identical results were expected. The variance between intensity of copper use, but discounting the offshore grid inter-connector, is 6.8%. Given the semi-quantitative nature of the methodology, we consider this as an acceptable degree of error.

The grid inter-connector on average consumes 11.44 tonnes per turbine, or 3.53 tonnes/MW nameplate generating capacity installed. Undersea cabling constitutes 82% of total copper use in offshore wind farms both on a per turbine basis and on a per MW basis at 7.43 tonnes/MW.

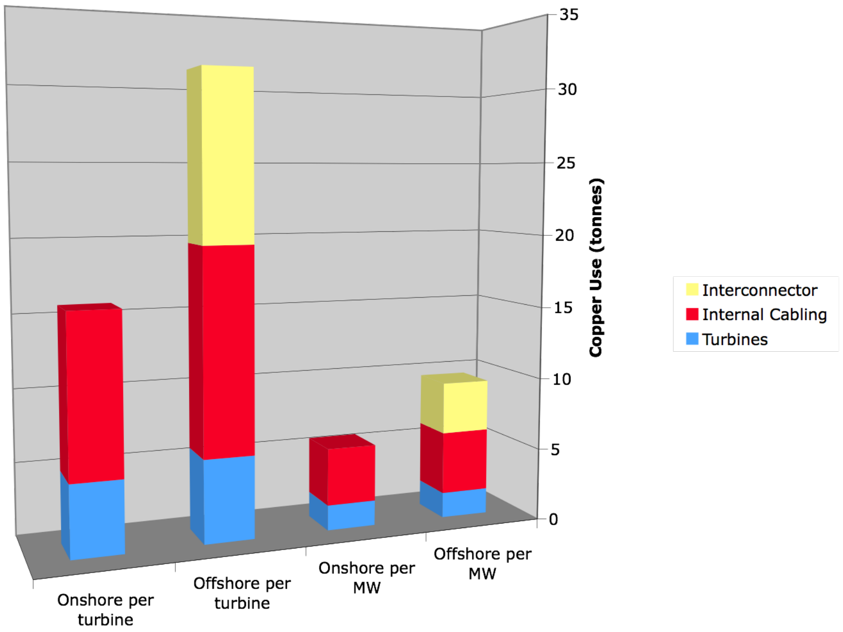

Figure 4: Graph showing a summary of copper consumption on per turbine and a per MW basis for both onshore and offshore wind farms split by component.

Total Copper Use In Wind Powered Generating Capacity Under Current UK Renewable Energy Strategy

As stated in the UK Renewable Energy Strategy, the current UK plan is to install approximately 37GW of additional wind powered generation capacity (12GW onshore, 25GW offshore) by 2020 with a further 10GW by 2030. We will restrict this analysis to the initial 37GW.

Using the current average copper intensity of 5.64 tonnes/MW we estimate that the new onshore capacity will require 67,680 tonnes of copper over the first 10 years (6,768 tpa).

If we use current average copper intensity for offshore wind farms of 9.58 tonnes/MW we can see a total copper requirement of 239,550 tonnes for new offshore installations with generating capacity of 25GW (23,955 tpa over the first 10 years).

The total copper requirement to achieve 37GW of new wind capacity is therefore 307,230 tonnes or 30,723 tonnes per year over the first 10 years, compared with total copper imports into the UK of 82,275 tonnes and scrap copper exports of 346,361 tonnes in 2007[33]. This would constitute a potential 37.3% increase in imports, if the copper were imported raw and all the components of wind turbines manufactured within the UK.

However, 2007 was an exceptional year when imports dropped by about 60% and a more representative import tonnage would be around 150,000 t (see Figure 5). This would adjust the potential increase in imports to 20.5% for 2007, against a background trend that would effectively see all raw copper imports cease in 2011.

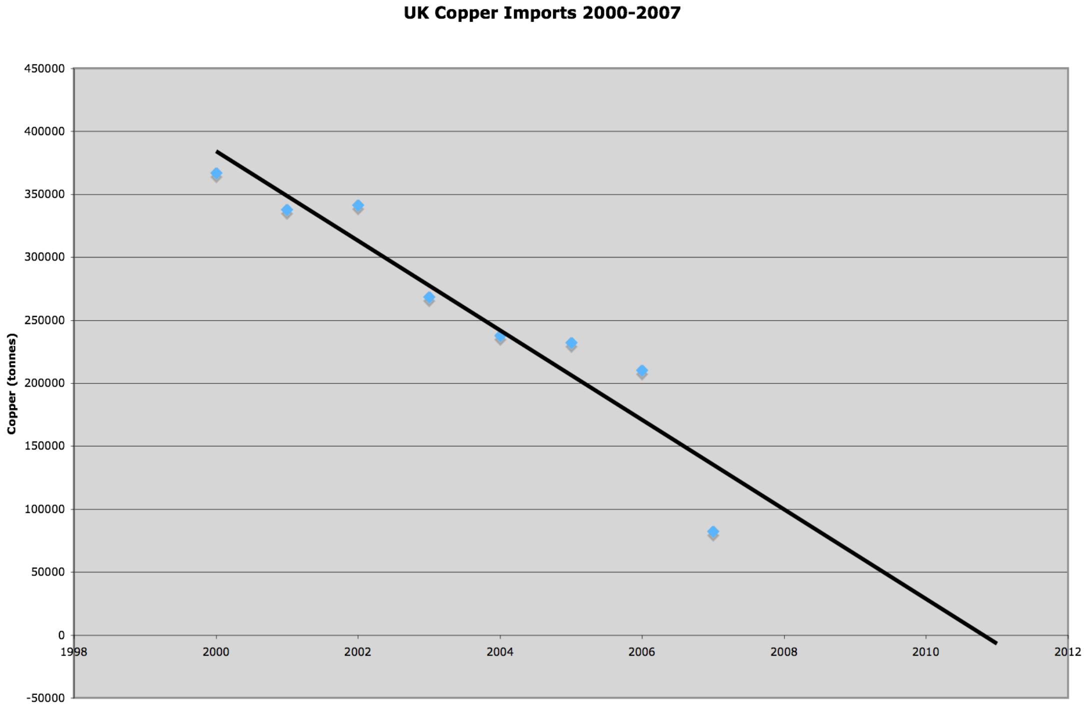

Figure 5: Graph showing the dramatic fall in copper imports in 2007 against a falling trend. Source - BGS, European Mineral Statistics 2000-2007.

Gross Financial Costs and Commodity Risk

In gross financial terms, at $8,862.58/tonne (the peak copper price achieved during 2008) the total cost of copper embodied in 37GW of wind powered generating capacity would be around $2.72 bn ($272 m per year) or £1.56bn (£156m per year).

If we compare that figure with the inflation adjusted historic average of $3,744/tonne[34] (1900-2004 adjusted to US$ in 1998), the gross cost of raw copper would be $1.15bn ($115m per year) or £657m (£65.7m per year).

This price variation could represent a significant source of risk in project development.

If considered in raw material terms, the cost of the copper is a relatively minor component of overall wind farm project costs. With wind powered generating capacity costing roughly £1m/MW onshore[35] and £2.5m/MW[36] offshore, even at $8,862/tonne, copper use would contribute $49,984/MW or 5% of total cost and $84,921/MW or 3.4% of the total cost respectively.

However, once copper containing components have been manufactured and delivered, costs associated with those components, but still excluding installation, rise as high as 21% of total offshore costs[37]. Clearly the main commodity price risk is in the component manufacture stage rather than the wind farm construction stage of copper's life cycle.

There are several ways to look at this issue and its relevance to the security of wind farm supply chains for the UK as a nation: we can take the view that as customers we should attempt to dictate the terms of sale so that no price volatility is passed on to us while maintaining relationships with multiple vendors, we could try and reduce price volatility, or we could accept market power and plan for price shocks. Clearly these are not mutually exclusive paths and policy-makers must choose the best balance to encourage.

While addressing issues surrounding the security of supply chains, policies are not inherently interventionist. However, in reality some policy intervention is usually undertaken to guarantee continuation of supply, even if it is simply increased monitoring of trade balances aimed at decreasing informational asymmetries and so decreasing the impact of short-run price speculation, identified by McMillan &

Speight (2001) as a component of non-ferrous metals price volatility[38].

By contrast long-term (multi-decadal) copper price volatility is relatively low and we could reasonably assume that as long as copper is required for wind powered electricity generation using today's copper-intense technologies that the price will tend to its long-term average of $3,744/tonne in adjusted for inflation to 1998 dollars. However, that is not the immediate concern since the UK government has decided that wind powered generating capacity is needed now in response to the challenge of climate change. What is most important is the next 10 years and the demands that will be put on copper supplies during that time span. We will discuss this in a later section.

Raw vs Embodied Copper in the Balance of Trade

We can see that the UK's planned expansion of wind powered electricity generation capacity will add significantly to its current copper requirements and that the tonnage of exported scrap copper could easily cover that increase. Statistics from the British Geological Survey already cited show that roughly 37% of exported scrap is clean, refined, new scrap copper. This equates to over 128,000 tonnes of copper per year, on 2007 figures[39], that needs little or no refining prior to re-use in new componentry, compared with a potential increase in demand of 30,700 tonnes per year arising from the UK's wind energy goals. However, at present the components of wind turbines that contain copper are, mostly, not manufactured in the UK so do not appear in the BGS mineral statistics. It is unknown whether they are tracked during the collation of UKTradeInfo import/export statistics since the published, consolidated data[40] does not show detail to that level.

The UK currently has very limited copper smelting and refining capacity, so is unable to produce large amounts of copper from ore and semi-refined copper (known as matte or blister copper). Based upon a simple projection of the decline in basic, raw copper materials that the UK imports, the industry will effectively be closed in 2011 (see Figure 5). It does however have a significant scrap recycling capacity, and manufactories capable of copper wire production, including at least one capable of sub-sea power cable construction (JDR Cables in Hartlepool).

There may be sound economic reasons why the imbalance between imports and recycling exists. With old scrap only commanding 25% or less of the price of standard LME cash buyer contracts[41] it may not be profitable for a seller (the party actually stripping the copper from the wind farm or other installation) to recycle old scrap copper in the UK. However, with new scrap worth 52% of LME copper cash buyer prices[42], currently leaving over $3,000/tonne margin for both buyer and seller to profit, it is less clear why there is not more new scrap recycling capacity. The seller in the case of new scrap is usually a factory making parts out of copper, so it is possible that the general decline in UK manufacturing means that investment in recycling capacity may not be seen as sustainable in the long-run.

At the risk of painting the same picture from 100 different angles, it appears logical that a capacity to construct cables for use in wind farms utilising a proportion of, probably new, copper scrap from other UK sources, would increase the national economic benefits attributable to wind farm expansion by reducing copper exports and cable import, and promoting a shorter, more local supply chain. Environmental benefits would also be promoted by reducing international shipping associated with copper transport for re-manufacture.

Closing the Loop: The Proportion of Copper Available for Recycling During Re-power or Decommissioning

This study has shown that buried copper cable could constitute a significant proportion of the copper used in wind farm installations and that most UK companies do not typically plan to recover that cable upon decommissioning or re-powering. In effect this copper is lost to the system and constitutes a consumption of non-renewable resources.

Onshore Wind Farms

Only one EIA was seen that explicitly stated that buried cabling was to be recovered on decommissioning, that of Dunmore Wind Farm in Northern Ireland. The majority of decommissioning plans stated that the owners would remove any structures to slightly below ground level before landscaping. Several EIAs explicitly stated that no cable removal was to take place in order to minimise ground disturbance. Others stated that access track-ways would remain as a utility post-decommissioning, from which can be inferred that co-located cabling would also remain.

In onshore wind farms between 8% and 76% of copper used per MW is in buried cabling, so that on a per installation basis, 31% of copper used is available for recycling on decommissioning or re-powering.

On a global dataset the proportion of copper available for recycling is also 31%. The low proportion of copper currently planned to be recycled is primarily due to the influence of a small number of very large onshore installations, as can be seen in Figure

6. These are the Whitelee Extension Phase 2, Lewis and Viking wind farms in Scotland. These installations appear to have a high sunk cost in terms of copper that will not be removed upon decommissioning under current plans. Removal of these three wind farms from the dataset results in onshore intensity of copper use dropping to 2.06 tonnes/MW and 67% of copper used becoming available for recycling.

The significant impact of these three wind farms on the onshore dataset suggests that they should be analysed more closely and the applicability of our model tested against real-world copper consumption data. A particular source of concern is the assumption that least cable length is used, rather than least cable cost, in these large and highly engineered projects.

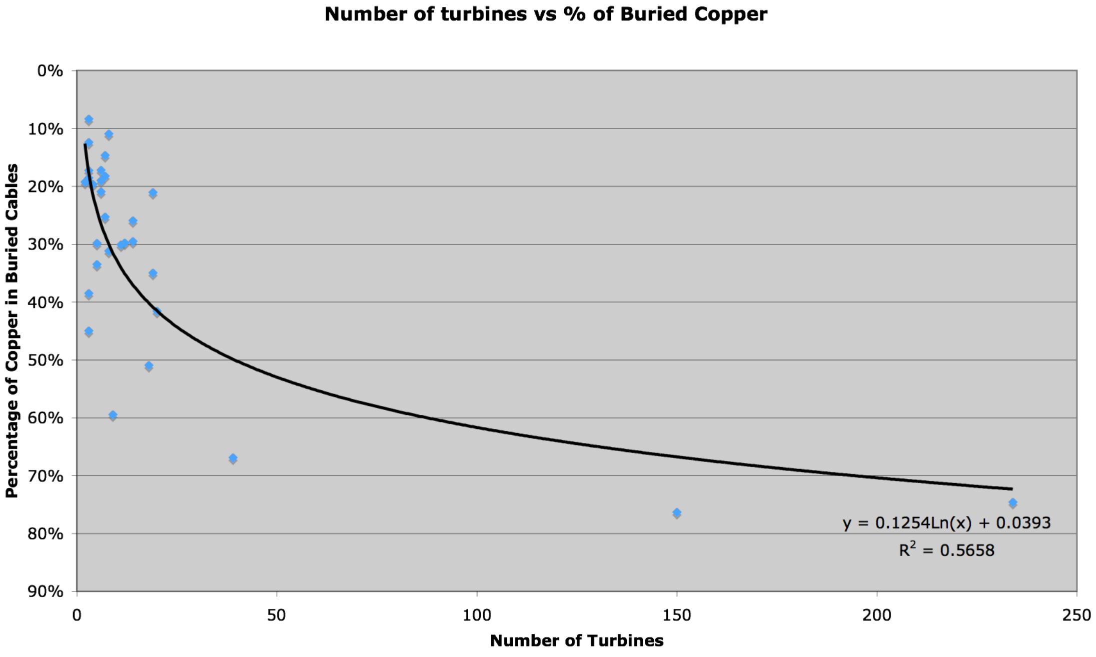

Figure 6: Graph showing the declining amount of copper currently planned to be recycled as the number of wind turbines in particular wind farms increases.

Offshore Wind Farms

The realities of offshore cabling mean that no cable recovery is likely when decommissioning or re-powering offshore wind farms.

Cables are generally laid less than 3m below the seabed. In many shallow seas this is a dynamic environment subject to significant bathymetric changes through time as sub-sea dunes and ripples migrate with tides, currents and storms. Where significant tidal scour is expected cables may be covered with ballast, but no discussion of possible mechanisms of cable recovery was seen in any documentation.

In addition to naturally occurring effects, during the multi-decade lifetime of these cables it can be expected that fouling with anchors and fishing nets may occur, and even for cables to be severed, repaired or replaced. In addition, the laying of later cables or pipelines that cross the inter-connectors may also restrict retrieval. For these reasons we do not expect any recycling of sub-sea cabling to take place without significant policy intervention. This position is supported by the London Array Ltd (2009) when it states "(London Array Ltd) intends to follow current industry standard by leaving both inter-array and export cables in-situ" [43].

As a result the copper available for recycling is currently restricted to the turbine components themselves. On a per installation basis this is a mean of 20.3% of copper used in offshore wind farms, with between 7% and 40% available in specific instances. On a global dataset the proportion of copper available per MW installed for recycling from offshore wind farms is 18% of the total used.

Put into gross copper consumption terms 215,314 tonnes of copper will be lost to the copper cycle as a direct result of current UK policies. At 2008 prices this would be approximately \$2.22bn (£1.27bn) worth of copper, most of which is due to be placed just under the seabed. The loss is not irretrievable until corrosion becomes prevalent, but it is unlikely that seabed cable mining will become an economic activity in the near future.

Intensity of Copper Use

Within Each Turbine

There is no clear trend in intensity of copper use as nameplate capacity rises within wind turbines in either offshore or onshore wind farms. Since our data uses a gross assumption that every turbine is essentially a scale copy with no technological improvements this is an expected result.

As previously discussed data on the copper use in multiple large turbine designs is required in order to refine this dataset.

Within Onshore Wind Farms

There is a relationship between the total wind farm generating capacity and its intensity of copper use, best described by a logarithmic function as shown in Figure 8, below.

It is unclear what the reasons are for this relationship, but with increasing wind farm size may come increasing financial risk which may in turn lead designers to include features that increase the intensity of copper use such as redundancy in cabling topologies.

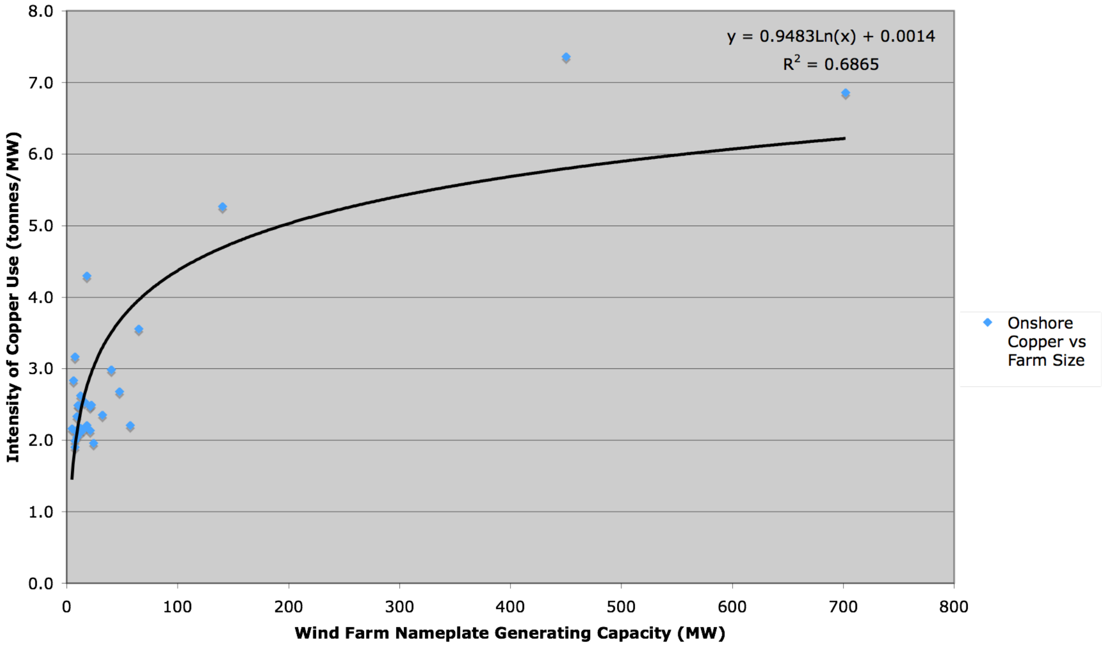

Figure 7: Graph showing the relationship between total wind farm generating capacity (MW) and intensity of copper use (t/MW). Source - Study.

Alternately, since there is a practical limit on 33kV cable cross-sections, mainly due to minimum radius of curvature requirements imposed by handling and transportation of cable reels, and a cost-benefit limit to their use, it may be that in the construction of larger onshore wind farms the cost of the sub-station outweighs the need for economy on the internal cabling. Simply put, there may be a cost limit on the number of turbines per cable, as well as an electrical current limit, above which it is cheaper to put in multiple cables that are longer but have smaller diameter copper conductors. This is precisely the kind of design detail that was sought from wind farm developers, but not given, and constitutes a significant deficiency in our theoretical model. To give a hypothetical example; take two planned onshore wind farms, on the same site, equal in every way except the number of turbines. Farm 1 has 15 x 2MW turbines and Farm 2 has 40 x 2MW turbines. Theoretically both could have single 33kV cable topologies connecting all of their constituent turbines to the sub-station. Alternatively Farm 1 could have 4 clusters of 10 turbines. The copper requirement difference between the two cabling topologies is 2.55 kg/m for 4 clusters of 5 vs. 13.44 kg/m for one string of 40 or 527%.

Clearly this is an ‘order of magnitude’ issue and a major problem with our model of onshore wind farm copper consumption as it currently stands, since our assumption is that minimum cable length will be used, not that minimum copper will be used or, the most realistic assumption, that minimum cost will be incurred. Fortunately even such an order of magnitude issue with onshore wind farms does not overshadow the general findings and does not affect analysis of offshore wind farm copper requirements.

Within Offshore Wind Farms

There appears to be a multi-modal distribution, shown in Figure 9, between offshore wind farm generating capacity and intensity of copper use with a distinct gap between wind farms of 325MW total generating capacity and those over 500MW generating capacity, and less distinct gaps between 150MW and 250MW, and between 500MW and greater than 600MW.

We can only suggest that this may be a function of commercial and financial pressures such as preferential terms for companies ordering over a certain number of turbines. It is also possible that licensing terms offered by the Crown Estate have contributed to this distribution, but without a time-based analysis that splits the wind farms on basis of licensing round and the terms offered by those rounds, it is impossible to reach a conclusion.

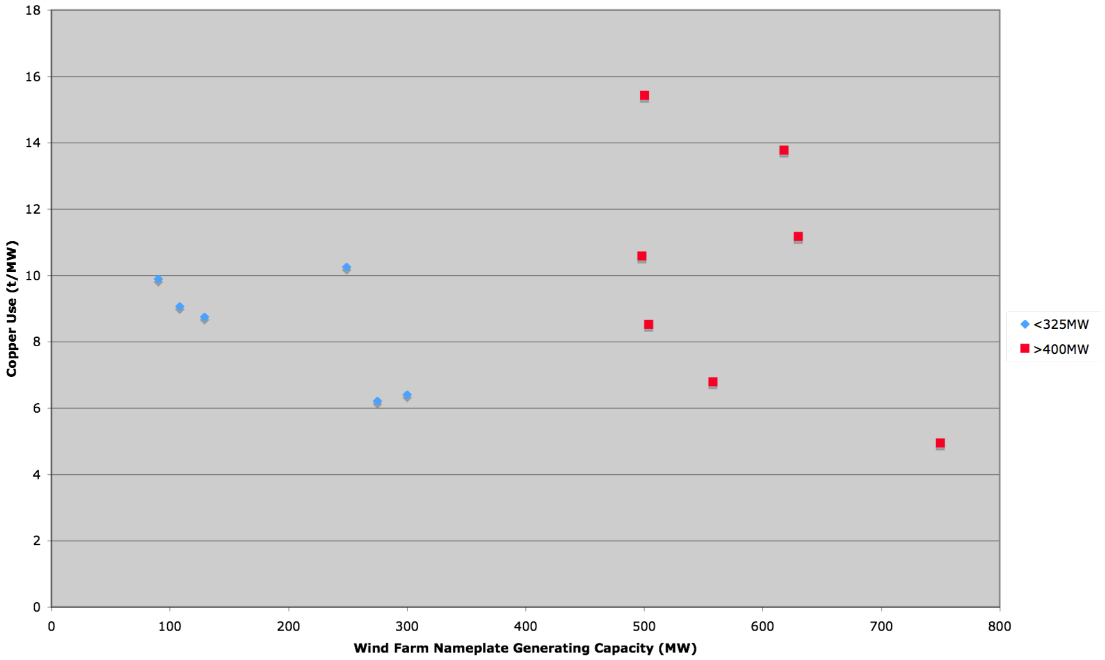

Figure 8: Graph showing the relationship between offshore wind farm generating capacity and intensity of copper use with data separated into two farm size classes. Source – Study

Offshore Wind Farms and Their Grid Inter-connectors

This study shows a positive relationship between the total intensity of copper use in offshore wind farms and the length of the grid inter-connector as shown in Figure 9. Please note that this is not necessarily the same as the distance of the wind farm to shore as several examples have been seen where a significant proportion of the connection to grid is after the cable reaches landfall or a route to shore is constrained by obstacles requiring that a longer than optimal route be taken. The relatively weak fit of the 'best fit' line may reflect the sinuosity of the inter-connector, but it was not within this study's remit to test this hypothesis.

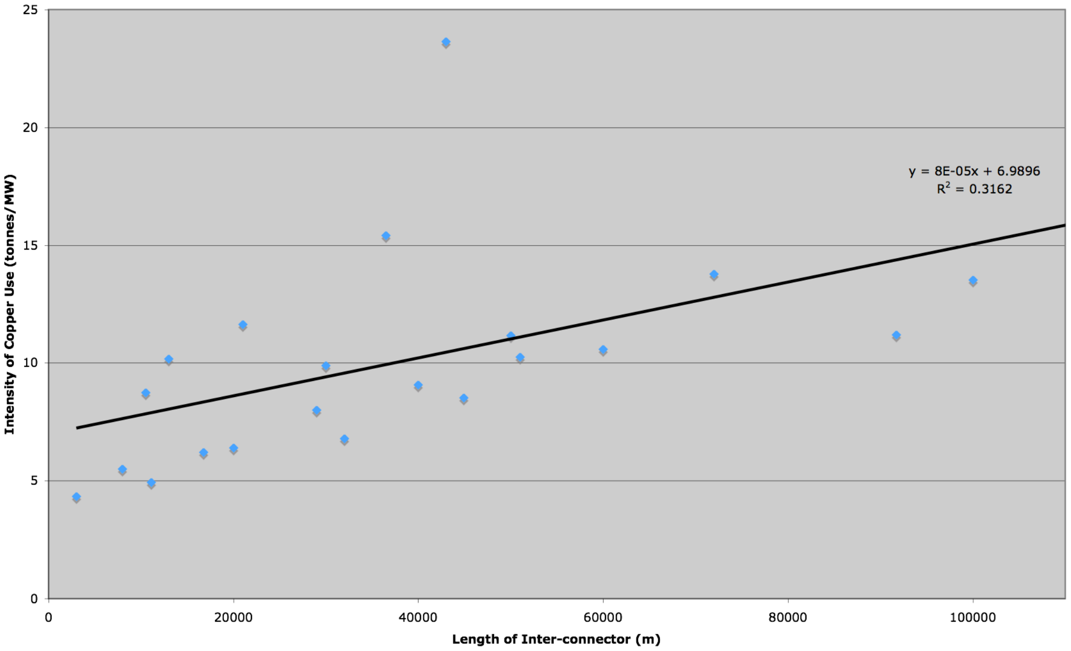

Figure 9: A graph of the intensity of copper use (t/MW) plotted against the length of offshore wind farm grid inter-connectors (m), showing a positive relationship. Source – Study.

There appears to be no capacity scaling benefit in terms of copper use within the inter-connectors in this study. This is to be expected, as the current carrying capacity of a copper conductor is a relatively simple function of cross-sectional area.

Our data shows that roughly a third of all copper used in offshore wind farms is contained in the inter-connector, irrespective of the turbine generating capacity or total wind farm generating capacity. This proportion ranges between 9% and 72%. On a global dataset the average proportion of copper use in the inter-connector is 33% of the total wind farm usage.

Clearly the grid inter-connector is an important component of offshore wind farms whose upward trend is influencing the total use of copper in wind powered electricity generation. There are at least two differing technological alternatives in development that have the potential to disrupt the current trend. These are high temperature superconducting cables and HVDC power transmission.

Analysis

An Overview of Global Copper Demand

In order to place the analysis of the data found by this study in context we must first introduce some of the current factors at play in the global commodities market and the copper market in particular.

The recent commodities boom saw copper prices rise over 300% in the 3 years to 2007, albeit from a historic low-stand, as shown in Figure 11, and the total commodities market value grow rapidly on the back of increased liquidity in Western Industrialised nations and rising demand from China and India[44]. The precise cause and effect of the sub-prime mortgage crisis, subsequent credit crunch and commodities crash is not important in this discussion, but the 2007-2009 recession has had, and will continue to have, a dramatic effect on metals markets by restricting credit to mining and metals processing companies, slowing development of new production capacity. In contrast, the development goals of China and India, and the global population growth trajectory, are not particularly subject to short-term market variance, however severe, and there is an expectation that economic growth within the natural resources sector will resume, possibly with even higher growth rates than before the recession.

However, we must remain critical of recent and developing global trends, and in the case of copper take a long view on both supply and demand.

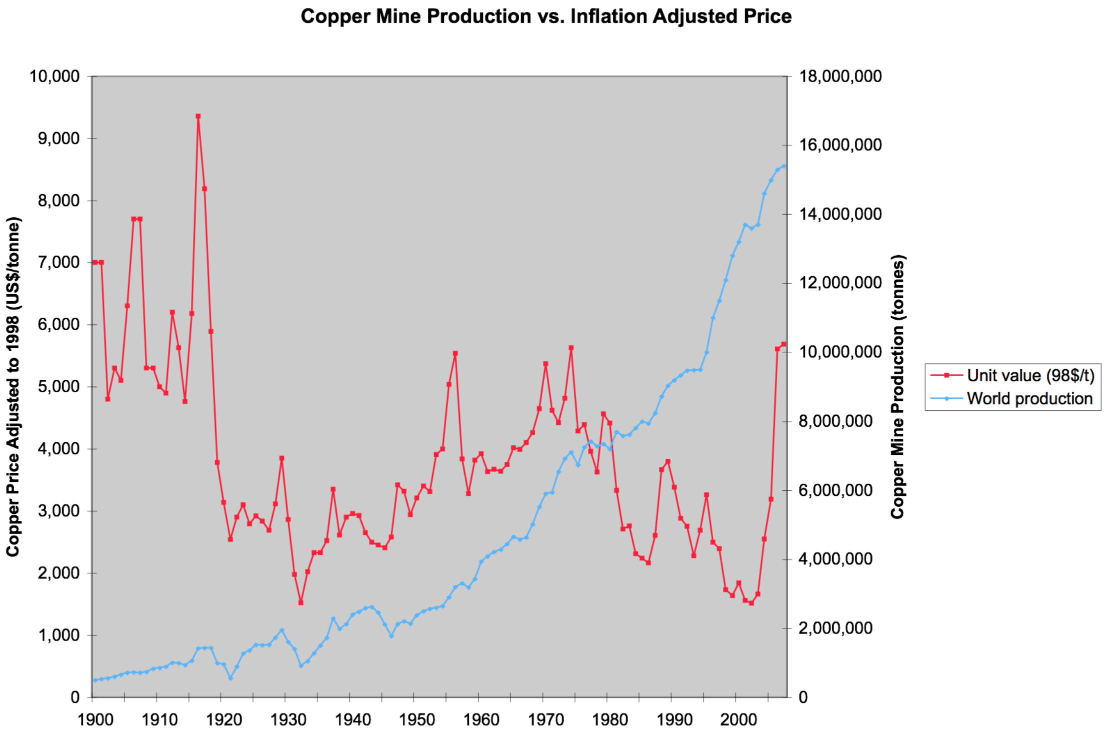

Figure 10: Graph of copper price in inflation adjusted US$/tonne (red) plotted against mined copper supply in tonnes (blue) for the period 1900 – 2007. Source – USGS.

Taking data from 1900 to 2007, we can see in Figure 10 that, although there are some periods where price and demand did correlate, for example during the period between 1929 and 1970, until very recently the gross trend was for declining relative copper price. This is believed to be primarily a function of increased efficiency in mining.

However, as we can see in Figure 10, recent price increases could signal a reversal in the trend shown since 1970. We can see that it took around 20-25 years of consistently rising copper prices between the end of WWII and the oil crisis and recession in 1973 before a significant growth rate change in both price and production occurred. These gradient changes coincide with the opening of several very large copper mines, mainly in the Americas, and the introduction of new processing techniques that are able to cope with lower and more mineralogically complex copper ores[45].

With the United Nations Population Division predicting that, under the most likely scenario, population will peak in around 2075 and at approximately 9.2 billion[46], a simple proportional increase using today's population (6.2bn) shows that copper demand would rise to somewhere around 24 M tonnes per year of mine production or around 1.42% per year compounded over 65 years. However, this assumes homogeneous intensity of copper use, and once the shifting patterns in development and urbanisation are factored in Kapur (2005)[47] demonstrates scenarios under which global copper demand increases between two-fold and nine-fold between 2000 and 2100. This equates to a hypothetical mined production of between 26.4M tonnes and 118.8M tonnes. Clearly a substantial increase in demand is expected which will provide a significant challenge to the copper supply.

The USGS currently estimate global resources to be approximately 3 bn tonnes. All three of Kapur's scenarios show peak demand following the hypothetical Kuznets curve with intensity of copper use varying with GDP. With copper intensity of use already falling in 'developed' nations, the majority of copper will be consumed in nations with growing GDP, so the multiplier effect of those nations also possessing the highest population growth rates cannot be ignored.

With global copper use at 2.6kg/capita per year in 2000 and forecast to reach a global average of around 5 kg/capita per year or higher by 2100, we can see that on a straight line 2065 shows a copper consumption of around 4.3 kg/capita per year. This equates to 39.9 Mt of copper per year or 75 years supply if the USGS resources of 3 bn tonnes are all proven and extracted. Taking into account that during the 65 years to 2075 the world will consume approximately 1.73 bn tonnes of copper, the remaining resources would total roughly 1.3bn tonnes or 32 years supply. On this analysis we do not forecast absolute depletion of copper supplies before peak global population is reached in 2065, irrespective of recycling rates. However, the effects of copper resource depletion would probably be affecting price and a sharper rise in global copper use could result in extreme pressure on copper supplies.

If we were in a technologically relatively static period as pertains to copper exploitation, as in the period 1945 to 1973, we could reasonably expect copper prices to rise in line with demand growth as shown above and be of the order of 1.5% per year. Taking the historic inflation adjusted average price of $3,744/tonne, copper price in 2075 would become around $5,620/tonne in 1998 US dollars but without allowing for future inflation. However, if we take the 2008 peak price as our starting point, copper prices in 2075 would be $13,298/tonne. We do not put these prices forward as a rigorous prediction since we do not believe that we are currently in a technologically stable period as regards the copper supply chain or those of its potentially disruptive competitor technologies, and that inflation will make adjustments for price equivalence necessary.

There is a bright side however. Once population peaks, the recyclability of copper means that very little copper mining should be necessary after that date, so long as high recycling rates are achieved. Taking this into account and substantially discounting equity, development, climate and emissions-based imperatives, an argument could be made that by not recycling copper now, but rather simply tracking it to ensure that its sinks and reservoirs are known, energy use can be minimised in the future when it is likely to become more expensive. This argument relies on a large degree of global copper market surveillance for its success, but could be scaled down to a country level, so long as that market and its dynamic were sufficiently well understood.

A Brief Explanation of Commodities Markets

Two major systems of metals trade co-exist at present; the exchange model and the bi-lateral contract model. Relatively few metals are traded in sufficient volume to support the administration necessary in the exchange model, though the advent of electronic trading platforms is changing the dynamic[48]. In contrast bi-lateral contracts can be made regarding any metal and they are made between a miner and a buyer who may be a consumer or, more likely, is a trader. A third possibility is the 'spot market' where relatively small amount of metals are traded for immediate cash delivery. The spot market is the market of last resort for end-consumers, where prices are almost always highest and volumes of metals available usually low. Within the industry spot prices are taken as indicative of sentiment rather than an accurate reflection of global average transaction prices.

The London Metals Exchange (LME) is widely acknowledged as the world's premier metals clearing house and the majority of metal prices are pegged to the price of contracts exchanged on its electronic trading platform. The free trading of contracts for future delivery (forward contracts) allows for a much larger volume of trade than the physical copper market and so allows for the risk that contracts will not be met to be distributed between many more market participants.

This so-called 'hedging' of contracts is a long-established mechanism within commodities markets and has real-world applications beyond the more recent buzz-word implications of high-risk, fast money.

It is still the case that ships carrying cargo are wrecked and that cargo is lost. The use of forward contracts allows for a miner to be paid for his copper before it is delivered, so allowing him to pay for the costs that he has already incurred and continue to mine for the next delivery. The buyer of that forward contract is betting that the contract will be fulfilled and that the copper can subsequently be sold at a price higher than was paid. If the contract is not fulfilled the buyer will lose out, so typically they will buy and sell those contracts many times over, each time gaining a small profit or loss, so that eventually the risk that no profit will be made on the delivery of a specific cargo of copper is very low. Since the spot or immediate delivery price of copper may rise or fall between the time of making the contract and its fulfilment, hedging can also be used to profit from speculation on the direction that prices may move and it is the recognition that this technique can be used in any freely traded market that has led to the explosion of so-called ‘hedge funds’ who also trade outside the commodities markets.

Over time it has become accepted practice that a miner may be able to raise finance to build a new mine or expand an existing one on the basis of selling their copper under forward contracts. This amounts to a loan secured against metal still contained in the ground and is termed the miner’s ‘hedge book’. It is sometimes announced that a mining company has closed its hedge book. This means that it has, in essence, paid off a loan, the interest on that loan being equivalent to the discount at which forward contracts are sold into the hedge book.

The second form of metals trading is under long-term bi-lateral contracts. The length of time and volume of metal covered by such contracts are confidential and contract specific. Contracts for iron ore are typically only one year long as demand can shift very quickly and the volume of ore that is delivered requires a great deal of space to store securely. Copper contracts can be longer since warehousing of ore and concentrate is not so much of an issue and the higher price that copper fetches supports more administration of stocks. The ultimate long-term contract would for a copper mine to be owned and run by a copper consumer, and while this can occur, especially in other even rarer metals, it is unusual. More common is for a consumer to take an equity stake in a large mine so that it can exert more control over its supply chain without taking the full risk of mine development.

This is a simplified overview of the copper market. It may seem that the long-term contract offers more price stability and predictability, so provides a more secure supply chain. That is true if the whole market for a metal is carried out under individual long-term contracts, but as soon as a reliable exchange is set up long-term contracts in any metal gain a large element of risk since they cannot be hedged against immediate supply/demand balances. The long-term contract is therefore the contract of choice for consumers who, for whatever reason, are risk insensitive. The ultimate risk is that they cannot use or sell metals that they have paid for and must pay for their secure storage.

However, since copper has such a high degree of recyclability, if we know enough about our copper usage we do not necessarily have to store raw copper metal in warehouses waiting to be used.

Oversight and Governance in the Copper Market

The existence of open outcry exchanges and reliance of the global copper market on those exchanges to set standards and minimise the financial risks of copper production is considered by most to be of benefit to the trade. However, the exchanges occupy a position of trust and so wield considerable power. These are commercial organisations run to make a profit for their shareholders and, while they are regulated, it is not generally with 'a strong hand'. The LME has, in the past been likened to a Gentleman's Club and accused of opacity and non-disclosure. There are reasons why this view is taken. Apart from a network of bonded warehouses and metal stocks held for trade, its main asset is its reputation so it is at pains to preserve that asset.

The exchanges carry out a valuable primary governance role organising the orderly exchange of contracts and delivery of physical metal. But they are not immune to manipulation, and periodically shifts in prices raise concerns about outside price influences. These mainly centre of the paper contract trade since the volume of that trade is so dominant.

On occasion a lone actor has been blamed for copper market manipulation, as in the two cases, shown below, of Yasuo Hamanaka and Liu Qibing.

Mr Hamanaka was a trader working for the Japanese conglomerate Sumitomo, who became known as 'Mr Copper'[49] after building up a dominant market position in both physical metal and future delivery contracts over an extended period in the early 1990s. Eventually market conditions shifted against his position and resulted in losses of over $2bn for Sumitomo. It was widely known what Mr Copper was doing and his positions, supported by loans fraudulently obtained from investment bankers, effectively propped up the copper price at a level where his company still made a profit. What wasn't known was that he was signing permissions to trade using his manager's names, without actually gaining their permission. So, while it is correct that it was his actions which resulted in large losses, both his employers and the institutions that subsidised the market manipulation were guilty of, at the very least, a lack of internal oversight as his forgeries went unchecked over almost ten years. Several fines were imposed[50] and amendments to trading regulations were effected after this manipulation was fully exposed[51]. Most notably contracts are now settled with cash, rather than the credit system that allowed Hamanaka to build his 'empire'. At its peak contracts and physical metals attributed to Sumitomo and Hamanaka totalled around 5% of world supplies. Upon discovery of this fraud copper prices fell by about 30% and, after a rally through 1997, remained at historic lows until 2004.

Liu Qibing was a trader on the LME for China's State Reserve Bureau (SRB) and created quite a stir in 2005[52] when he appeared to over-sell 200,000 tonnes of copper from China's stockpile, essentially selling copper that informed spectators suspected didn't exist[53], before disappearing from London never to be seen on the trading floor again[54]. There has been no formal announcement of any actions taken against Mr Liu or the trading company that he worked for, though it is reported that he was jailed on his return to China[55]. The LME has not announced any actions arising from this case.

We can see that despite learning hard lessons the exchange system is still not perfect and that individuals, with the complicit support of large institutions through lax oversight, can still have dramatic effects on world copper markets. To a certain degree this lack of strong oversight may be seen as a function of the relative importance that governments place on the trade that is carried out, and we would question whether sufficient independent oversight is given to the commodities trade given that it is the ultimate basis for all other trade and industry.

The Future Availability of Copper

We hope that we have shown that under current policies the continuing supply of new copper into the UK economy, whether it is embodied in wind farm components or in raw metal form, is an essential component in achieving policy goals regarding wind energy. A discussion of possible threats to the security of that supply is therefore essential to any analysis of the proposed system.

In this section we will examine the possible and probable areas of risk and discuss relevant policy mechanisms to minimise or eliminate those risks.

Risks to Mined Copper Output

The risks in mining, in terms of geological occurrence and grade variation, will be taken as inherent in that part of the copper supply chain since this study is primarily aimed at a policy level and there is no mechanism for policy-makers to influence those variables. Suffice it to say that individual mine output is not completely predictable and that mine operations can be highly sensitive to metals price and mining cost variations.

However, in general terms we can surmise that more mines located in more jurisdictions are better than fewer mines and more geographically focussed mining activity, when it comes to continuity and predictability of total supply. Reducing concentration of political control over supplies of a specific metal, reducing the economic influence of a specific geographic area over metals markets or even reducing exposure to climatic variation can all reduce commodity supply risk, so potentially raising the overall security of supply.

Governments that have the potential for native copper mine production therefore have a choice over whether to encourage that primary industry or to rely on international trade and recycling to provide for any economic strategies or ambitions that they may have. The UK has chosen not to encourage copper mining in the UK over the last 20 years and as a result has no current copper mining capacity, though one small pre-production copper-zinc-lead mine does exist on Anglesey[56].

The corollary of this discussion is the increasing prevalence of resource nationalism, whereby a nation's government takes whole or partial control of its natural resources[57], excluding international ownership to the point of delivery or export. In an economic climate where increasing competition for resources is foreseen, this is an attractive option for many governments though historically it has been argued that this route has not been beneficial to the mining industry's efficiency.

Long-term Copper Availability

Copper has a history of continual technological use for over 7000 years[58] and, though the advent of electrification has greatly expanded its scope and volume of use, the technologies used in its production have kept pace with demand and even resulted in an inflation-adjusted fall in copper prices during the 20th century.

Over recent years extensive analysis has been undertaken on the long-term availability of metals in general and copper in particular, with two essentially opposing theories being expounded. On the one hand proponents of the finite resource model, as put forward by workers such as Gordon et al (2006)[59] consider the global abundance of metals as a function of geology and their use as being limited by total lithospheric concentration. This group can foresee a day when all metal available on Earth is contained within a recycling pool and its endless use is only limited by energy availability and recycling efficiency. Ayres (1993)[60] terms the extreme interpretation of this view as ‘neo-Malthusian’ and sees its emphasis as being on “restraint, austerity and government-led equity”, with some opponents seeing it as anti-technological.

The opposing faction, exemplified by Tilton and Lagos (2006)[61], appear to see the neo-Malthusian view as ignoring the full role of markets in promoting alternative technologies and substitution that would, in effect, price certain metals out of use, so always retaining some primary availability to be mined in the future. Boulding (1966)[62] terms this view ‘Spaceship Economy’ and its proponents as emphasising the need for cooperation and conservation.

Both arguments have their merits and to a large degree both are right, and wrong. The main difference in their points of view seems to be their stances towards time and energy. The first group appear to see the time and energy required for long-run sustainability to be boundless, while the second group see time and energy availability to be bounded and for that to define the system in which we must live. If we put the argument into economic terms Gordon et al use an implicit discount rate of zero percent when considering sustainability of metals supply and the needs of future generations, while Tilton et al use a value greater than zero.

While decisions made on the basis of one or other of the two different theories can have serious real-world effects on the way that metals are treated by policy-makers, these are essentially philosophical differences that cannot be resolved conclusively by scientific study. Irrespective of how much evidence is brought to the table by either side, in conclusively testing the theory as it applies to metals availability the earth's crust would need to be analysed in its entirety rendering sustainability, in other ways, an impossibility.

From a responsible policy-maker's perspective however, the choice is clearer. They must consider that energy availability at least is bounded, so making the second, market-oriented interpretation of resource availability the more realistic and providing re-assurance that copper will not run out within their period of office or that of any of their immediate successors. However, as we have shown above there are risks attached to that view in terms of intensity of copper use up until peak global population is reached and the responsible policy-maker should attempt to minimise those risks. This could include expounding a neo-Malthusian view in order to motivate action in certain sectors of the economy.

Security of Supply = Price Predictability

As we have argued above, while the amount of copper on the earth is finite, we do not suggest that the global economy is in any immediate danger of exhausting all supply of this extremely useful and valuable metal.

It is well accepted within the mining and minerals processing communities that metals production is a function of price, with increasing metal prices encouraging technological development, substitution and exploration for new reserves. Concerns about security of supplies of copper should therefore focus on price predictability rather than being overly dedicated to divining the precise number of years of geological reserves that are currently left in the ground.

Note that we do not suggest that price stability is an absolute requirement; merely that sufficient information exists so that appropriate contingencies may be put in place to allow for continuation of supply. Even high degrees of price volatility may be planned for with, for example, larger stockpiles or constraints on speculative investment. What is more difficult for supply chains to cope with is not knowing that a commodity price may be volatile. To paraphrase the incomparable Donald Rumsfeld, it is the 'unknown unknowns'[63] that cannot be planned for.

The established global market for copper is resilient and currently appears to cope reasonably well with both supply and demand-side shocks. The production costs and benefits are passed on to the consumers relatively effectively, even if the socio-economic and environmental costs are not. There are alternatives to copper in most areas of its use though, at present, copper offers the best price/performance in most high volume industries where it is used. Since the industrial revolution there has always been copper available in the global market though at some points in time, including the latest commodities boom, demand has driven prices so high that copper scavenging and theft have become significant factors[64].

Predictable Factors in Global Copper Demand

We have discussed at reasonable length the rising copper demand imposed by development and population increase, but there are other predictable factors contributing to copper demand.

Currently it is predictable that, if ambitious plans to move national energy systems towards electricity and away from hydrocarbons materialise[65], as well as those strategies that aim at moving electricity generating systems towards generating capacity that could be more copper intensive, such as wind power, then demand for copper may rise from its current levels.

The Need for Intelligence

As the UK moves to a low carbon energy system and its target of 15% renewable energy powered electricity generation (ibid) it will place increasing reliance on wind power and the supply of the materiel to generate electricity from it. A logical extension of the UK's energy security policy would be to monitor and evaluate the supply chains that its re-configured energy system will become reliant upon. This commodities intelligence capacity already exists for coal, oil and gas, and data is published regularly in the Digest of UK Energy Statistics (DUKES) series[66]. It is also well established for copper and other metals used in the energy system, where the British Geological Survey produces the authoritative European Mineral Statistics (EMS) series[67], though the nature of these commodities and the resources given over to their analysis means that data lags behind the traditional energy minerals. For example, the publication of the EMS is annual or bi-annual, meaning that the current issue contains data up to the start of the current economic downturn at the end of 2007.

The only other public organisation in the OECD freely publishing data of this resolution and scope is the USGS in its Mineral Commodities Series[68]. Commercial organisations such as CRU Group[69] and Platts[70] provide minerals intelligence to the paying public, but it does not appear wise to contract out critical intelligence capabilities, especially in a time of increased sensitivities towards raw material supply[71].

Though the nature of metals trading and the manufacture of energy capture devices, such as wind turbines, mean that most metals supply chains are less time-sensitive than those of fuel-based energy systems, where stockpiles have a limited capacity, an increased minerals intelligence capability seems prudent if the nation's energy security is to be seen in consistent terms.

The Possible Future of the Copper Trade

This study has shown that real-world recycling rates within wind farms will be desperately low in the UK if decommissioning and re-powering is carried out as specified in the majority of EIAs. An initial suggestion would be to change planning guidance or waste disposal/site rehabilitation guidance to increase the proportion of copper recovered.

This is an area of global concern as copper waste and mixed electronic waste containing significant amounts of copper is close to becoming considered a commodity in its own right that is traded and transported before recycling into 'fresh' metal. As copper prices increase, the price of copper scrap will probably also increase[72]. While copper scrap is not currently exchanged under formalised and tradable contracts pegged to the metals prices at exchanges such as the LME, we see no reason why a situation should not arise whereby any material, whether considered waste or ore, is traded on the basis of its metal content.

Considering the UK's 'Copper Reservoir' as a Strategic Mineable Resource

If we assume that the supply of copper to the UK's energy system is critical to the implementation of the new wind energy strategy, then the copper currently embodied in UK capital could be considered a strategically important reservoir that can be tapped in the same way as a stockpile, albeit one with a longer lead-time than conventional stockpiles.

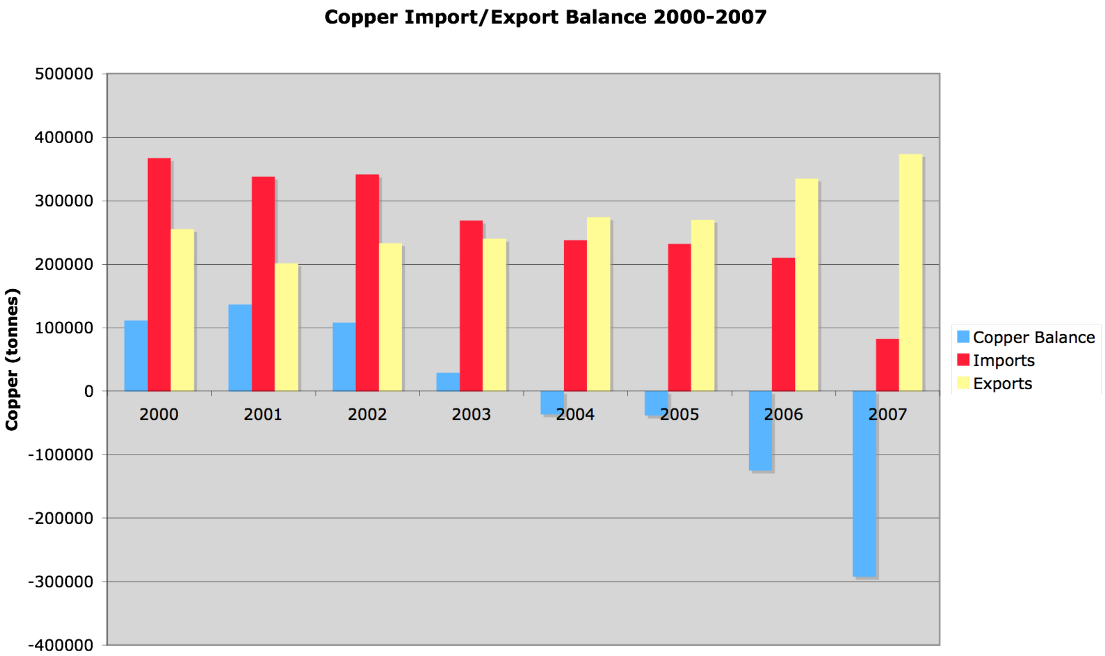

Figure 11: Chart showing the balance between copper import and export. Data source - BGS European Mineral Statistics 2000-2004, 2001-2005 and 2003 - 2007.

In Figure 11 we can see that this reservoir is currently being depleted by a net outflow of copper from the UK. The primary mechanism for that depletion is the export of scrap copper for recycling. A rise in the proportion of copper recycled is a good thing in terms of global energy use and environmental impact, however in terms of the UK's economic well-being we can also see that imports are falling, and have been over the course of this seven year dataset. Not only is the UK's copper reservoir being depleted, but copper is being exported as scrap; a low value commodity that is traded at a discount to 'fresh' refined copper. This could be seen as a lost opportunity in economic terms[73]

It would be an interesting and useful exercise to carry out a materials flow analysis to establish where the UK's copper reservoir is located in order to further tailor policy towards this valuable metal, but it is one that is beyond this study. For example, the recent car scrappage scheme that incentivised potential buyers to update old domestic vehicles for newer more fuel efficient ones[74] could be repeated for specific items that have a known copper embodiment, so liberating an increased amount of old scrap copper for specific purposes. Alternatively an environmental liability could be imposed on wind farm developers that did not recover old cabling.

Is not apparent from the consolidated data available, the degree to which copper is transferred embodied in manufactured items and what contribution that this makes to the import/export balance. This would be a very time consuming task for government to undertake as it would require a materials inventory for every product bought or sold in the UK. However, product manufacturing standards and disclosures could go some way to achieving it at a European level in a similar way to that seen with ISO certification, where suppliers come under pressure from business customers to show their own certification in order to establish a chain of quality assurance.

Alternatives to Copper for Wind Powered Generating Capacity

There are currently several technologies available to reduce the intensity of copper use in wind farms and their grid connectors.

We have spoken of HVDC transmission that, in addition to having a lower copper footprint by using two rather than three conductors to support the same current as 3-phase HVAC, has lower transmission losses over long distances[75]. This technology has been implemented for long distance power transmission and has been proposed for a number of large offshore wind farms.

Super-conducting cables have been proposed as a way of further reducing transmission losses. They would also contain less copper as the conductor itself is replaced, though screening surrounding it may not be. Super-conducting cables are being laid in South Korea to replace a major HV transmission network in Seoul[76], but would require additional research and development before installation in a UK offshore wind farm.

Recently high temperature super-conductors have also been used as an alternative to copper windings on generator rotors. The UK-listed company Zenergy is specifically marketing its HT super-conducting coils as suitable for inclusion in generators to be used by wind turbine manufacturers as a way of producing the same power from a generator that is significantly lighter[77]. This allows tower construction to be lighter, or indeed taller by reducing the total weight of the nacelle, or for turbines to be significantly smaller but still output a similar amount of power.

Direct drive generators are now being implemented that remove the need for a gearbox between the turbine rotor and the generator. Though the copper contained in wind turbine gearboxes is a relatively minor constituent, the removal of the gearbox also removes a significant proportion of total power losses in the turbine assembly.

Effectively more power is output for less copper, so the intensity of copper use drops on a per MW basis.

Copper Intensity of Consumption and Recycling Rates

We have shown that the current design and planning constraints on UK onshore wind farms allow roughly 30% of the copper that is used in their construction to become available for recycling upon decommissioning or re-powering (or 70% if the large wind farms are not considered). However, if the current UK old scrap copper recycling rate of 5% is applied, only around 3.5% of the total copper that is used in new onshore wind farms will be re-used.

On this analysis 5.4 tonnes of copper is effectively consumed per MW of installed nameplate capacity. This consumption is split between re-powering and decommissioning timelines, with 1.7 tonnes consumed at every re-power with the remaining copper, in the form of buried cabling, still useful until decommissioning.

In offshore wind farms the situation is worse. With only 18% of the embodied copper available for re-use, potential recycling drops to under 1% of total use. Put into context, only around 9 kg of every tonne of copper used in offshore wind farms will be re-used at current UK copper recycling averages. The recycling will again be split between re-powering and decommissioning, though since we are not aware of any offshore wind farms that have undergone either process we will make no assumptions on how that will play out.

Copper Intensity and Cable Repair

There is another factor that must be considered in wind farm copper consumption; the possibility of cable damage and need for repairs or replacements to be carried out. For the purposes of this analysis we will ignore the possibility of deliberate malicious damage to wind farm cabling as this is a common factor in all electrical power distribution systems irrespective of the energy source and falls into a separate field of security analysis.

Though cable damage is possible in onshore wind farms, the repair or replacement of any cable would require that a trench be dug. It would therefore be logical to dig the old cable out and replace it in the old trench to minimise cost and environmental disturbance. This would make recycling of the cable a trivial matter, and indeed make its responsible disposal a matter of legal requirement, as it would be considered industrial waste once recovered. We therefore consider cable damage not to be a major net consumer of copper in onshore wind farms.

In offshore wind farms the situation is different. There is the potential for damage to the cables by an exogenous event whether it is a storm, shipwreck, entanglement with fishing nets or damage due to a dragged anchor. A sufficiently damaged cable on a large wind farm may be cheaper to replace than to repair and in this situation we would expect no recovery of the damaged cable to take place. Though in reality repair costs would need to be in the $10s of millions of dollars before this would be considered. If we take an exogenous piece of evidence to support this conjecture, while specially designed cable laying[78] and even cable repair ships exist, we have found no evidence of any ships specifically designed to recover large amounts of cable. Cable recovery operations do happen and specialist companies exist to facilitate it[79], but the lack of specialist capital assets to support the activity suggests that it is not undertaken very often.

Possible Policy Adjustments and Future Work

The distorting effect that the three Scottish super wind farms have on the onshore dataset is a cause for concern and we have discussed possible reasons for the results obtained by our model. Taken in context of this first pass study, the result is useful in highlighting the possible difference between multiple small installations and monolithic installations in terms of resource usage, but the potential variance between different models constructed in terms of cost rather than copper should not be ignored.

Irrespective of degree, at present the ethos appears to be to 'design in' copper consumption when wind farms are constructed in the UK. The policy to develop offshore wind powered generating capacity accentuates that stance towards copper use and effectively exports the environmental and energy consumption impacts of its production to the countries where copper is mined and refined. We understand that re-powering provides the opportunity to recover the majority of copper embodied in the turbines themselves, so we hope that recycling rates far exceed those stated here using UK industrial averages. However, we did not pursue that line of investigation and will leave confirmation of recycling rates during turbine re-powers to other workers. That data may be sparse at present since relatively few re-powers have occurred onshore in the UK and none have occurred offshore as far as we can tell.

Relatively small changes to planning requirements in the development of onshore wind farms could maximise copper recycling rates in these installations. Recovery of shallow buried cables from engineered ground works is an activity that takes place in quarries in the UK on a regular basis, often overnight and undertaken by thieves[80], and can be achieved with minimal environmental disturbance and cost, so we believe that it is technically feasible to recover onshore cabling in the majority of cases. We suggest that some research into low cost-low impact cable removal techniques be made.

However, the trend towards larger offshore wind farms further from shore may swamp the benefit that might be seen from the proposed changes to recycling policy shown above. The technical challenges involved with recovering sub-sea cables are likely to be extremely costly to overcome and we do not anticipate that large-scale sub-sea cable recovery will be an economically viable prospect in the near future. Given that the majority of offshore wind farms are less than 10 years old and have operating life spans of 25 years or more, consideration of the economics of cable recovery in conjunction with forward copper price curves beyond 15 years in the future should be made and the potential for cable recovery built into current designs.

A first step towards sub-sea cable recycling would be recovery of the internal cabling, which is more likely to be free from fouling or overlying services due to the establishment of shipping and development exclusion zones around the turbines themselves. The inter-connectors are more problematic as they will usually traverse areas that are open to shipping and, necessarily, will pass close to shore where tide and wave action can be stronger and more difficult to overcome.

We believe that serious consideration should be given to the long-term sustainability of using copper inter-connectors for offshore wind farms. The advent of HVDC for long distance sub-sea electrical transmission should reduce total copper consumption, but it will not eliminate it. High temperature superconducting cables may offer a better long-term solution, so long as the raw materials from which they are constructed are not supply-constrained in the same way as copper.

Consideration should also be given to alternative methods of energy export from wind farms that are located far offshore, or have long and circuitous cable routes to the nearest grid connection point. Alternatively activities that require electrical power could be moved to the turbines if it is viable to do so, completely removing the requirement for an inter-connector and freeing the offshore wind farm from the economic constraint of its construction and maintenance. Whether any such activities exist is not known at present.

Conclusions

We hope to have shown convincing evidence that wind powered generating capacity, and especially offshore wind powered generating capacity, will be a significant consumer of copper in the UK in coming years and that under current UK policy this will increase the UK's copper requirement substantially.

We do not doubt that sufficient copper exists to satisfy the demands of a shift in UK energy policy towards known low carbon energy sources, such as wind, in the period to 2030. However, we do not believe that current UK policy is set up to minimise the economic, environmental or social impact of that shift and the lack of strategic thought towards metallic resources means that the UK will effectively be paying twice for the copper that it will need in coming years. In gross financial terms this may not have the same impact as, for example, the depletion of UK oil reserves, but copper is one element of many that is under increasing demand from many different industries, and the cumulative impact of competition for a new set of energy-related materials may have unpredictable effects in terms of political and economic stability on a global scale.

Copper is not a unique or isolated resource. No one country produces more than 35% of the world's copper and its occurrence is relatively widespread with copper mined on every continent bar Antarctica, though its abundance is low. However, its production is linked by geological occurrence to the vast majority of molybdenum, rhenium and tellurium supplies. These metals are rapidly gaining 'popularity' in the changing energy world; with molybdenum used as a steel additive in corrosion-resistant pipelines, rhenium used in high temperature gas turbine blades and tellurium contained in some thin-film solar cells. Changing the economics of copper, by increasing the proportion of recycling and so discouraging primary mined supply, would also change the economics of these associated metals and policy-makers should consider carefully the possible knock-on effects of influencing natural resource supply chains without a full understanding of the potential network effects.

The UK hosts a unique minerals intelligence capability, both in terms of an expert government-funded body in the shape of the British Geological Survey, but also in world-leading private companies such as the London Metals Exchange and CRU Group, as well as a significant body of knowledge within the mining consultancy and minerals finance community. It seems strange therefore that, publicly at least, government policy shows so little appreciation of metals supply chain issues. The general withdrawal of government from the metals supply chain in previous years may have led to an incomplete understanding of the mining and minerals sector at a time when demands on that supply chain are thought to be contributing to global economic instability. It may be worth noting that Wen Jiabao, Premier of the PRC, is a geologist by training and experience[81] and we put this forward as a possible endogenous factor in China's contrasting policy stance on mined commodities, notwithstanding the very different politico-economic development track that China is on.

This study has highlighted the apparent disregard that UK policy shows to copper as a finite resource. It is currently used as a consumable commodity, with government policies and industry practices both encouraging that consumption. Yet a central plank of the UK's energy and economic strategy, increasing reliance on offshore wind power, looks set to increase its use over and above established demand.

Building imbalances into the UK's copper trade whilst simultaneously basing a new energy system on that metal looks reckless and could put development of the UK's new low carbon energy system at risk in the period to 2030.

There are a number of technical and policy-led mechanisms that could slow the rate of increase in copper use or even reduce the intensity of copper use in wind powered generating capacity, for example the use of HVDC for transmission in offshore wind power, the proposed pan-European offshore super-grid, or new policies on the recovery of buried cables. However, it seems very likely that copper use will increase in the UK for at least the next 20 years as the UK government's wind-focussed renewable energy strategy is implemented, and that this will set its economy into competition for resources, especially with those countries undergoing mass electrification and urbanisation.

In recent years the UK has dramatically reduced its manufacturing capacity and almost eliminated its non-ferrous metals processing and refining capacity. We would encourage policy-makers to consider the whole-system benefits of the current policies towards scrap export and recycling in the period to 2030, by which time the majority of new wind powered generating capacity should have been installed. It is possible that the UK's copper reservoir could reach its peak at that time and, effectively, no further large-scale imports of copper would be necessary if the correct balance is struck between import, exports and recycling in the run-up to that time.

We would also encourage investment in non-copper conductors whose life-cycle performance and impact is at least equivalent to the red metal.

In the longer term the concentration of copper into structures that have a known location within the UK could be seen as a strategic national hedge against substantial copper supply risks in the future, approaching peak global population in 2075. The establishment of easily accessible potential copper 'mines' in the form of wind farm power cables may have benefits in the longer run, but we would question the wisdom of establishing that reservoir under water where corrosion may take place. We have seen no evidence of this degree of strategic thought within current UK policy, but cannot rule it out since no privileged information has been used in this study.

Seen in terms of the neo-Malthusian and Spaceship Economy views on finite resource availability, current UK policy towards copper use in wind power appears (maybe inadvertently) to stand somewhere in between the two, but lean towards the Spaceship Economy view espoused by Tilton et al. Current policies that have the effect of encouraging copper to be buried on UK territory seem to take the view that the UK should grab as much copper as possible before mined copper is priced out of reach and concentrate it in recyclable form. But the driving force behind the change to a low carbon energy system, and hence wind power, is very definitely neo-Malthusian in ethic.

It is possible that in attempting to balance these two opposing views, contradictory policies have been put in place whereby wind power is promoted but at the expense of apparently increased copper consumption. That, in effect, short-term market variance is deemed an acceptable risk so that copper supplies are secured in the period approaching 2075. The alternative interpretation is that current policies are simply mis-designed where the future of copper supplies is concerned.

Appendices

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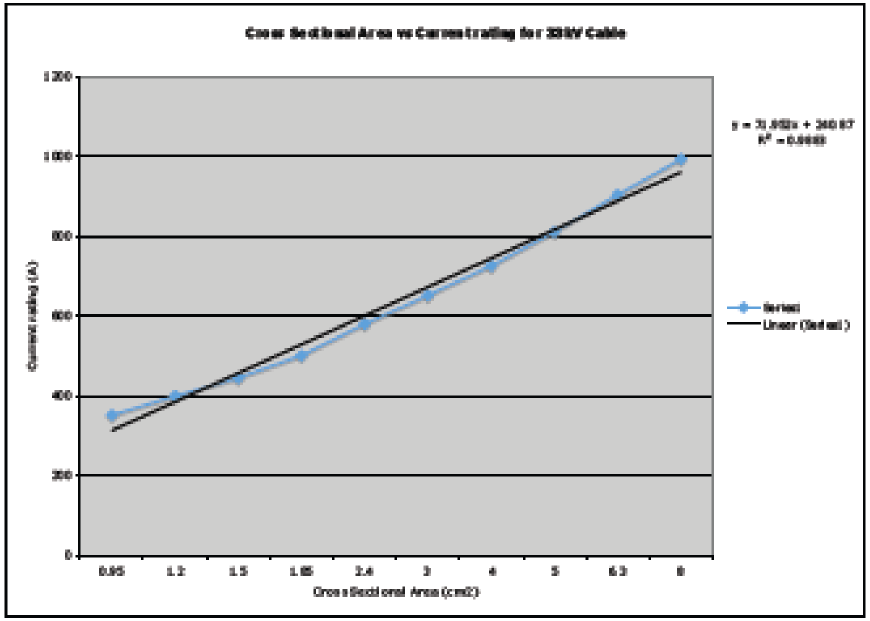
Appendix One - Matrix of 33kV Cable Specifications

Power Calculations
Nexan 33kV 3-core submarine cable

Conductor	Single Conductor Cross Section (cm2)	Current Rating (Amps)	Max Current under 3-phase AC (A)	Total 3-core Cross Section	Mass of copper (kg/m)
1x95	0.95	352	1829.05	2.85	2.55
1x120	1.2	399	2073.26	3.6	3.23
1x150	1.5	446	2317.48	4.5	4.03
1x185	1.85	502	2608.47	5.55	4.97
1x240	2.4	581	3018.96	7.2	6.45
1x300	3	652	3387.89	9	8.06
1x400	4	726	3772.41	12	10.75
1x500	5	811	4214.08	15	13.44
1x630	6.3	904	4697.32	18.9	16.93
1x800	8	993	5159.78	24	21.50

Using Power = Current * Voltage (assuming harmonic AC)

Rated Power Output (MW)	On a 33kV circuit	Max Current (A)	Max 3-phase Current (A)
0.5	33000	15.15	26.24
0.75	33000	22.73	39.36
1	33000	30.30	52.49
1.5	33000	45.45	78.73
2	33000	60.61	104.97
2.3	33000	69.70	120.72
2.5	33000	75.76	131.22
3	33000	90.91	157.46
3.6	33000	109.09	188.95
4	33000	121.21	209.95
4.3	33001	130.30	225.68
5	33000	151.52	262.43
6	33000	181.82	314.92



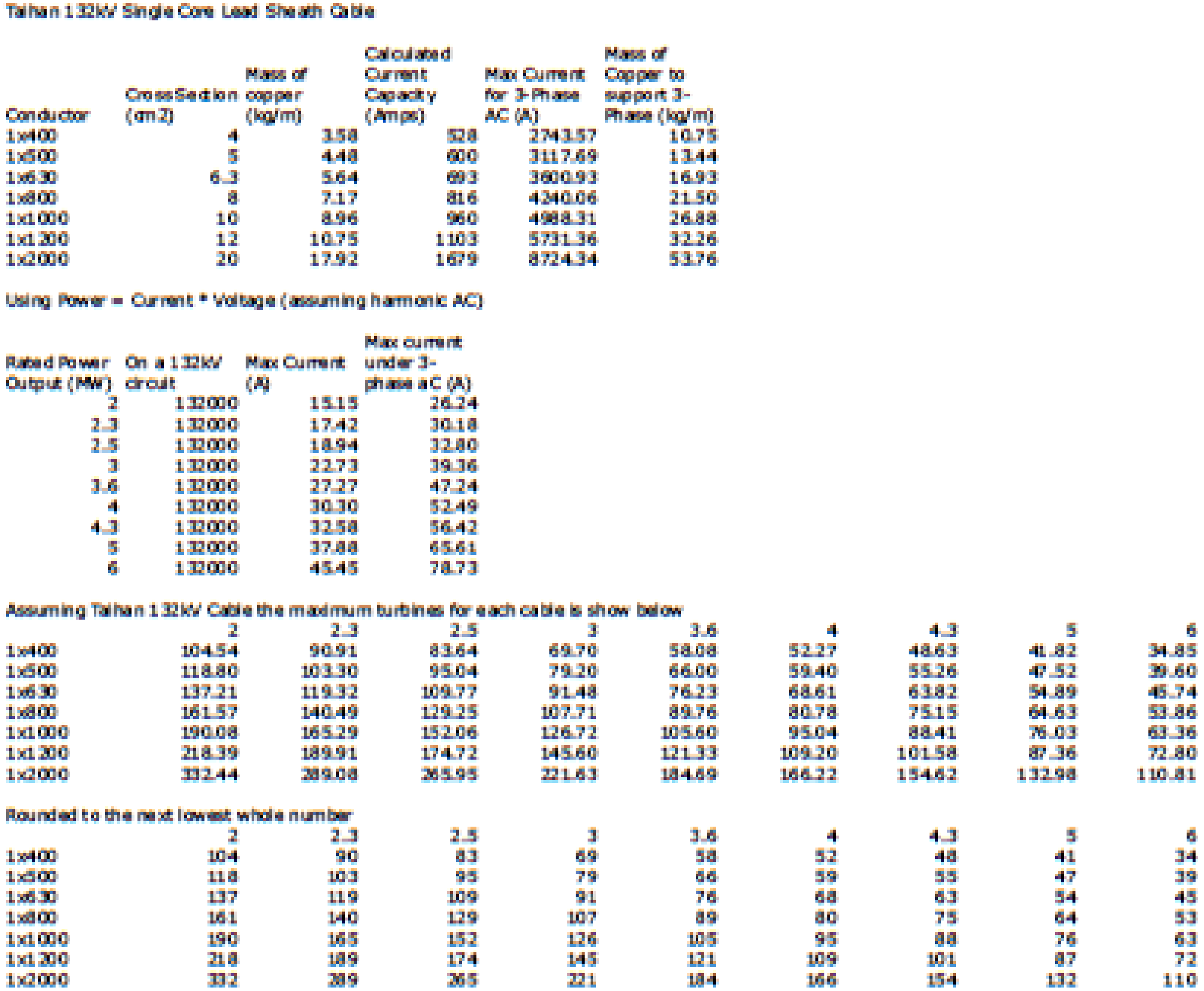
Assuming Nexan 33kV 3-core cable the maximum turbines for each cable using 3-phase AC is

	0.5	0.75	1	1.5	2	2.3	2.5	3	3.6	4	4.3	5	6
1x95	69.70	46.46	34.85	23.23	17.42	15.15	13.94	11.62	9.68	8.71	8.10	6.97	5.81
1x120	79.00	52.67	39.50	26.33	19.75	17.17	15.80	13.17	10.97	9.88	9.19	7.90	6.58
1x150	88.31	58.87	44.15	29.44	22.08	19.20	17.66	14.72	12.27	11.04	10.27	8.83	7.36
1x185	99.40	66.26	49.70	33.13	24.85	21.61	19.88	16.57	13.81	12.42	11.56	9.94	8.28
1x240	115.04	76.69	57.52	38.35	28.76	25.01	23.01	19.17	15.98	14.38	13.38	11.50	9.59
1x300	129.10	86.06	64.55	43.03	32.27	28.06	25.82	21.52	17.93	16.14	15.01	12.91	10.76
1x400	143.75	95.83	71.87	47.92	35.94	31.25	28.75	23.96	19.97	17.97	16.72	14.37	11.98
1x500	160.58	107.05	80.29	53.53	40.14	34.91	32.12	26.76	22.30	20.07	18.67	16.06	13.38
1x630	178.99	119.33	89.50	59.66	44.75	38.91	35.80	29.83	24.86	22.37	20.81	17.90	14.92
1x800	196.61	131.08	98.31	65.54	49.15	42.74	39.32	32.77	27.31	24.58	22.86	19.66	16.38

Rounded down to the next lowest whole number provide a safety margin

	0.5	0.75	1	1.5	2	2.3	2.5	3	3.6	4	4.3	5	6
1x95	69	46	34	23	17	15	13	11	9	8	8	6	5
1x120	79	52	39	26	19	17	15	13	10	9	9	7	6
1x150	88	58	44	29	22	19	17	14	12	11	10	8	7
1x185	99	66	49	33	24	21	19	16	13	12	11	9	8
1x240	115	76	57	38	28	25	23	19	15	14	13	11	9
1x300	129	86	64	43	32	28	25	21	17	16	15	12	10
1x400	143	95	71	47	35	31	28	23	19	17	16	14	11
1x500	160	107	80	53	40	34	32	26	22	20	18	16	13
1x630	178	119	89	59	44	38	35	29	24	22	20	17	14
1x800	196	131	98	65	49	42	39	32	27	24	22	19	16

Appendix Two – Matrix of 132kV Cable Specifications



Taihan 132kV Single Core Lead Sheath Cable

Conductor	CrossSection (cm2)	Mass of copper (kg/m)	Calculated Current Capacity (Amps)	Max Current for 3-Phase AC (A)	Mass of Copper to support 3-Phase (kg/m)
1x400	4	3.58	528	2743.57	10.75
1x500	5	4.48	600	3117.69	13.44
1x630	6.3	5.64	693	3600.93	16.93
1x800	8	7.17	816	4240.06	21.50
1x1000	10	8.96	960	4988.31	26.88
1x1200	12	10.75	1103	5731.36	32.26
1x2000	20	17.92	1679	8724.34	53.76

Using Power = Current * Voltage (assuming harmonic AC)

Rated Power Output (MW)	On a 132kV circuit	Max Current (A)	Max current under 3-phase aC (A)
2	132000	15.15	26.24
2.3	132000	17.42	30.18
2.5	132000	18.94	32.80
3	132000	22.73	39.36
3.6	132000	27.27	47.24
4	132000	30.30	52.49
4.3	132000	32.58	56.42
5	132000	37.88	65.61
6	132000	45.45	78.73

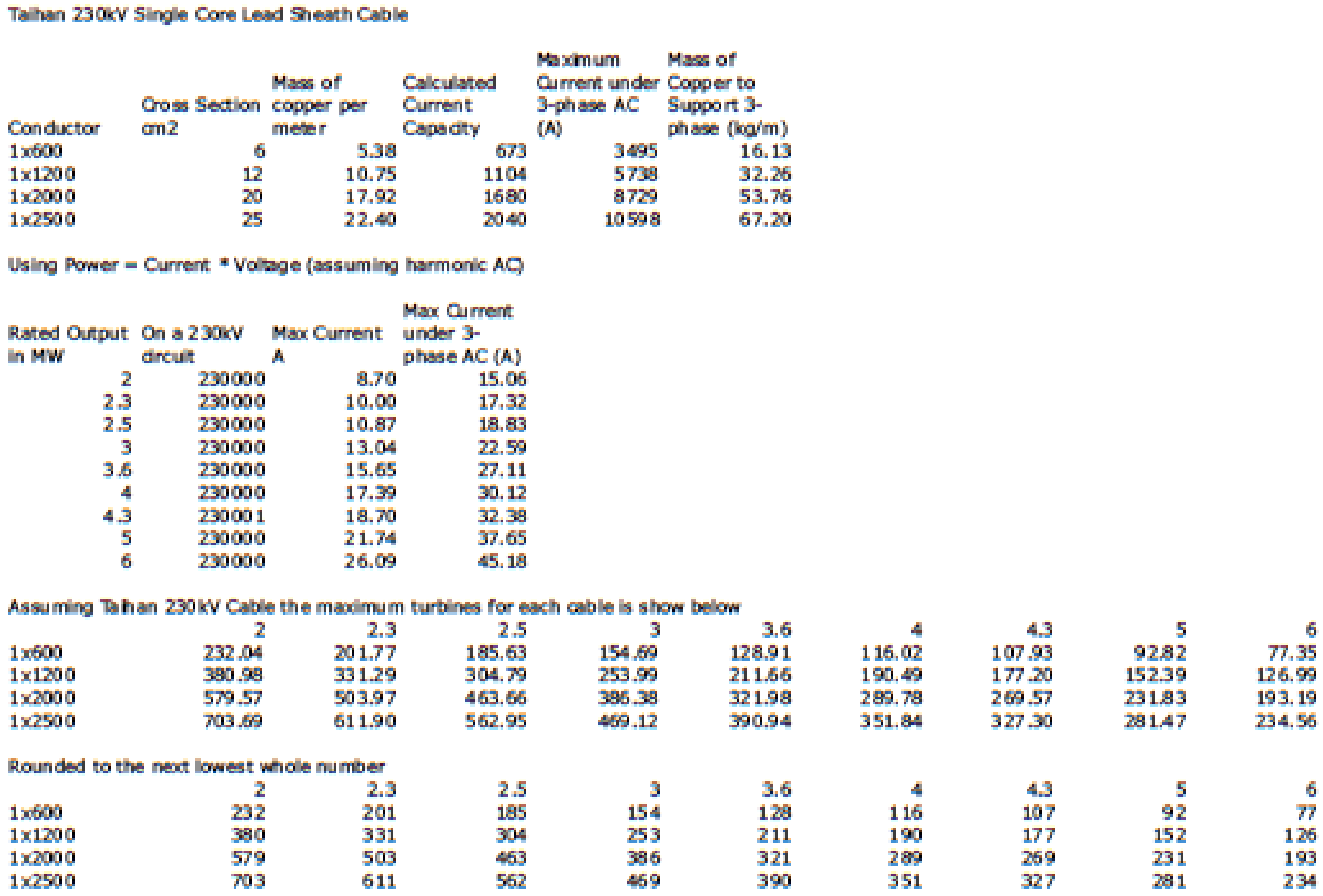
Assuming Taihan 132kV Cable the maximum turbines for each cable is show below

	2	2.3	2.5	3	3.6	4	4.3	5	6
1x400	104.54	90.91	83.64	69.70	58.08	52.27	48.63	41.82	34.85
1x500	118.80	103.30	95.04	79.20	66.00	59.40	55.26	47.52	39.60
1x630	137.21	119.32	109.77	91.48	76.23	68.61	63.82	54.89	45.74
1x800	161.57	140.49	129.25	107.71	89.76	80.78	75.15	64.63	53.86
1x1000	190.08	165.29	152.06	126.72	105.60	95.04	88.41	76.03	63.36
1x1200	218.39	189.91	174.72	145.60	121.33	109.20	101.58	87.36	72.80
1x2000	332.44	289.08	265.95	221.63	184.69	166.22	154.62	132.98	110.81

Rounded to the next lowest whole number

	2	2.3	2.5	3	3.6	4	4.3	5	6
1x400	104	90	83	69	58	52	48	41	34
1x500	118	103	95	79	66	59	55	47	39
1x630	137	119	109	91	76	68	63	54	45
1x800	161	140	129	107	89	80	75	64	53
1x1000	190	165	152	126	105	95	88	76	63
1x1200	218	189	174	145	121	109	101	87	72
1x2000	332	289	265	221	184	166	154	132	110

Appendix Three – Matrix of 230kV Cable Specifications



Taihan 230kV Single Core Lead Sheath Cable

Conductor	Cross Section cm2	Mass of copper per meter	Calculated Current Capacity	Maximum Current under 3-phase AC (A)	Mass of Copper to Support 3-phase (kg/m)
1x600	6	5.38	673	3495	16.13
1x1200	12	10.75	1104	5738	32.26
1x2000	20	17.92	1680	8729	53.76
1x2500	25	22.40	2040	10598	67.20

Using Power = Current * Voltage (assuming harmonic AC)

Rated Output in MW	On a 230kV circuit	Max Current A	Max Current under 3-phase AC (A)
2	230000	8.70	15.06
2.3	230000	10.00	17.32
2.5	230000	10.87	18.83
3	230000	13.04	22.59
3.6	230000	15.65	27.11
4	230000	17.39	30.12
4.3	230001	18.70	32.38
5	230000	21.74	37.65
6	230000	26.09	45.18

Assuming Taihan 230kV Cable the maximum turbines for each cable is show below

	2	2.3	2.5	3	3.6	4	4.3	5	6
1x600	232.04	201.77	185.63	154.69	128.91	116.02	107.93	92.82	77.35
1x1200	380.98	331.29	304.79	253.99	211.66	190.49	177.20	152.39	126.99
1x2000	579.57	503.97	463.66	386.38	321.98	289.78	269.57	231.83	193.19
1x2500	703.69	611.90	562.95	469.12	390.94	351.84	327.30	281.47	234.56

Rounded to the next lowest whole number

	2	2.3	2.5	3	3.6	4	4.3	5	6
1x600	232	201	185	154	128	116	107	92	77
1x1200	380	331	304	253	211	190	177	152	126
1x2000	579	503	463	386	321	289	269	231	193
1x2500	703	611	562	469	390	351	327	281	234

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