Saving reed lands by giving economic value to reed

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SUMMARY

Discussions about the need for renewable energy, the need for nature conservation, the need to double the world's food production to eliminate hunger, the need to reduce carbon dioxide emission, and the wish to reduce dependency on dwindling oil resources, show that these issues are intimately related and sometimes mutually exclusive. The use of food crops for the production of renewable fuels has resulted in the energy *vs*. food debate; the use of scarce land and fresh water for the dedicated production of biomass conflicts with food production and nature conservation; the collection of harvest residues and forest wastes as biomass to produce renewable fuels is complex and leaves a CO_2 footprint.

The several species of reed that grow naturally in deltas, river plains *etc*. can provide large amounts of biomass but are hardly mentioned in the debates. Harvesting reed does not threaten the nature and the natural functions of reed lands, which are carbon neutral or carbon dioxide sinks. Reed production does not need extensive infrastructure or complex cultivation and does not compete with food production for land and fresh water. Reed lands in many places are under threat of reclamation for economic activities and urbanisation. This trend can be countered if reed is seen to have a proven economic value.

In this article I argue that giving a sustainable economic value to reed lands can only be realised if the exploitation is recognised as being environmentally acceptable, commercially feasible and a source of economic gains for all stakeholders. Commercial feasibility can be achieved under present economic conditions only if a reliable supply of considerable volumes of reed at a limited price can be guaranteed.

KEY WORDS: bioethanol; biomass; *Phragmites australis*; renewable energy; salt-tolerance

INTRODUCTION

Reed: its positive and negative features

The term "reed" is used for a multitude of species, varieties and phenotypes of grass-like plants that occur naturally in waterlogged and inundated places. Reeds propagate through rhizomes and seed. Most species form thick layers of rhizomes on the surface and in the upper soil layers and form thick layers of root mass mixed with soil particles**.**

Reed grows naturally and produces large amounts of biomass under diverse climatic conditions in deltas, on lakeshores, in canals, channels and drains, in natural and canalised rivers, and in almost any natural or man-made marshy area. The area covered by reed worldwide is large but there is no known global inventory, although Köbbing *et al.* (2013) estimate the global area of *Phragmite*s alone at between four and ten million hectares (40,000–100,000 km^2).

The most relevant reed species belong to the family Poaceae (common reed *Phragmites australis*, giant reed *Arundo donax*, canary grass *Phalaris arundinacea*, Burma reed *Neyraudia reynaudiana*). I include other species as 'reeds' in the broad sense: family Cyperaceae (papyrus *Cyperacea papyrus*); family Typhaceae (bulrush/cattail *Typha latifolia* and *T. angustifolia*), family Restionaceae (Cape thatching reed *Chondopetalum tectorum*).

Reeds thrive in waterlogged and inundated areas with little competition from other vegetation, so that the stands are practically homogeneous. Reed lands are often part of valuable wetland ecosystems; they serve as grazing areas, resting and breeding places for birds and protect fish and crustaceans (Yamian *et al.* 2012). Many reed-covered wetlands are classified as nature reserves. Reed lands have many, not always obvious, natural functions such as: protection of river banks and lakeshores against erosion and wave action, purifying the water that flows through them including the removal of oil residues (Mandi *et al*. 1996, Ji *et al.* 2004), and storing large amounts of carbon (in the reeds above and below ground) that could otherwise potentially be released to the atmosphere as greenhouse gases (GHG), mainly carbon dioxide (CO_2) and methane (CH_4).

Harvested reed has traditionally served humanity as material for roof thatching, for heating, for the production of mats, baskets etc., and as traditional building materials. Since antiquity reed has served as a raw material for pulp and paper-making (De La Cruz 1987).

Invasion of reed and spontaneous reed growth may, however, be a nuisance, especially in areas where humans have modified nature for their own purposes. Several species can be invasive. Examples are cattail *(Typha latifolia*) invasion in the Senegal River Valley after the building of a dam, and *Phragmites australis* invasion in the Midwest of the USA (Chambers *et al.* 2003).

The reed that grows in watercourses often reduces or obstructs water flows and indirectly promotes sedimentation. In extreme cases the sedimentation can, over time, cause a rise in topographical level and eventually lead to drying of the reed lands. The conveyance and navigational functions of reed-infested watercourses have to be maintained by regular clearing and possibly dredging. Especially in tropical climates, which have an uninterrupted growing season, frequent and costly clearing of waterways may be required. The development of deltas and the construction of river dams have increased the occurrence of reed infestations in undesired locations.

Large reed-covered areas, especially those in deltas and river plains, are under threat. These areas, often strategically located along waterways, are and have historically been choice areas for agricultural and economic activities, resulting in the establishment and growth of villages and towns. Population growth coupled with increasing urbanisation results in unrestricted urban development combined with economic, industrial and, where possible, agricultural and horticultural activities. One of the many consequences is pressure to reclaim the reed lands for urban expansion as well as for agriculture and industrial development. A secondary effect of the reclamation of reed lands is that the stored carbon is released as GHG and the carbon depositories are destroyed (Wichtmann 2006). An example is the negative effects of reclamation of peatlands in past centuries, many of which were, at least partly, dominated by reed. These areas emit GHG and lose fertility. They experience continuing subsidence due to the oxidation of the soil organic matter. The subsidence causes increasing problems and costs in maintaining the desired water levels. Re-wetting peatlands which are subsequently covered with reed will not only produce reed, but will also preserve the peat by minimising further oxidation of the organic matter, thus minimising release of GHG (Wichtmann 2006, Barz *et al*. 2007).

In the long term, large areas of permafrost peatland are expected to thaw when the expected climate change increases average temperatures. The thawing will result in oxidation of the organic matter in the soils with consequent releases of GHG. This, in turn, will accelerate climate change (Anonymous 2012a). Since many of these areas will initially be marshy and waterlogged, covering the area with reed (if reed does not grow spontaneously) will minimise the oxidation and subsequent release of GHG.

The growing demand for renewable resources, the reduction of GHG emissions and the conservation of nature areas

The realisation that oil resources are rapidly being depleted, that climate is negatively affected by large increases of GHG emissions and that valuable nature areas are being reclaimed and destroyed by a growing world population, has given rise to a search for renewable energy resources, renewable raw materials and methods to conserve nature areas.

Reed lands yield large amounts (3–25 t ha^{-1}) of dry biomass that can be used for renewable energy (Wichtmann 2006, Barz *et al*. 2007, Ash 2009) and as renewable raw materials. The harvesting of reed biomass by removing the aerial parts of the reed stimulates regrowth and does not damage the reed land as a whole.

Physical and commercial conditions vary widely in place and time, and the purpose of this article is to point out the commercial potential of reed as a renewable resource in general. The numerical values given are estimates of average values based on information provided by official sources, published literature, consultants' reports and studies (grey literature) and the author's knowledge and experience. Many of these sources are not published, or are partly confidential information from industry and technology providers. Consequently, the values used must be reconsidered for each individual situation.

Despite the strong arguments for saving reed lands there is, in places, considerable pressure to reclaim reed-growing areas for urban and industrial expansion. The interests of local people who traditionally use reed for small-scale and cottage industry or grazing are unlikely to be regarded as sufficiently important to withstand this pressure. Giving economic value to the reed lands by economically exploiting the reed is, then, an incentive to preserve the reed lands and at the same time to preserve their many natural functions that are beneficial for nature and humanity.

Once commercial organisations are convinced that relatively large-scale use of reed as a raw material for the production of energy, biofuels, pulp, building materials (fibreboards), possibly soil improvement products like biochar (Anonymous 2009) and textiles is technically possible and economically profitable, a credible counterforce against reclamation will be created. Nature conservation objectives are often seemingly at odds with economic or commercial uses of nature areas, so commercial parties tend to be hesitant about initiating activities in reed lands, even if these are not classified and/or they are convinced that nature is not damaged by their activities, in order to avoid political and legal conflicts. Therefore, strong governmental support is required to convince commercial parties and other stakeholders of the non-controversial potential benefits of the exploitation of reed.

In what follows I consider the comparative advantages of reed as a renewable resource, the practical aspects of its exploitation, the challenges of large-scale reed production, and the conditions which must be fulfilled to stimulate commercial interest in reed production and processing.

CHARACTERISTICS OF REED AND ITS GROWING CONDITIONS THAT ARE RELEVANT FOR ITS EXPLOITATION

Growing conditions and exploitation of reed compared with conventional crops

The differences of growing conditions of reed with other plants and crops are these.

- Reed can grow under inundated and waterlogged conditions and survives temporary or seasonal droughts. No precise data are available, but most species can thrive in areas with water depths of at least 0.5–1 m above the soil surface. Reed grows in areas where other (productive) plants cannot grow or thrive without reclamation and elaborate and expensive infrastructural and managerial measures. Consequently, reed does not compete with food crops for land.
- The Indirect Land Use Change (ILUC) factor records the change of land use consequent on using land to grow industrial (energy) crops and thus creating the need to grow food crops in other hitherto uncultivated locations, thus provoking their CO_2 emission (Laborde 2011). The factor for reed in its natural habitat is consequently zero.
- Some reed species (*Phragmites, Neyraudia* and, to a lesser extent, *Arundo donax*) are salt-tolerant and can grow under brackish and saline soil/water conditions, which often occur in coastal areas and parts of river deltas (Matoh *et al*. 1998, Mauchamps & Mesleard 2001, Croon 2013). Consequently, such reed does not necessarily require additional fresh (irrigation) water for its growth and is thus not in competition with food or fibre crops for the increasingly scarce freshwater resources.
- Reed propagates naturally through rhizomes and natural seeding. After harvesting there is natural re-growth from the rhizomes. Reed farming consists in practice of harvesting only; soil cultivation, re-planting, fertiliser and pesticide applications are not required. This dramatically limits the costs and the conventional energy requirements of cultivation, along with the associated GHG emissions.
- Harvesting and subsequent exploitation of reed can, at first glance, appear to contradict the objective of conserving reed beds and the nature areas where they grow. In autumn most of the nitrogen and phosphorus in the leaves is translocated to the rhizomes, so winter harvesting removes mainly carbon. In practice, regular winter harvesting of the reed is not known to be detrimental to reed growth and the natural functions of reed beds (Alsbury 2010). Summer harvesting can, however, reduce regrowth somewhat. To a certain extent regular winter harvesting can even be beneficial for the long-term conservation of reed beds. Examples are the reed beds in northern and central Europe that have been harvested for centuries to provide roof thatching materials, and the extensive reed beds in China´s coastal areas and lakes that are traditionally harvested for heating, building materials and paper production (Anonymous 2006). The reed in some wetland nature conservation areas in China is regularly harvested without negative effects. Recent publications come to the same conclusion, although some authors suggest two-yearly harvesting (Fieldfare 2000, Ikonen & Hagelberg 2007, Alsbury 2010, Pattuzi *et al*. 2012). Regular winter harvesting seems to promote more vigorous growth and perhaps to reduce the build-up of organic material in and on the underlying soil which causes the topographical level to increase. Thus, exploitation (harvesting) of reed does not need to conflict with nature conservation objectives for reed-covered wetlands.

Yields of reed

In the literature (for instance Thevs *et al*. 2007) the dry mass yield of reed ranges widely from around 6 to 40 t ha^{-1} yr^{-1}. Information from the Red Sea coast even mentions yields of 60 t ha^{-1} yr^{-1}. Yield is a function of species, climate, soil and water conditions that ranges, on average, between 10 and 15 t ha^{-1} yr^{-1}. Research and observations have proven that higher yields are possible with better varietal selection and/or adjustments/improvements of the growing conditions. From experience and observations, additional research can be expected to produce increases in yield with relatively simple measures. Current yields of 10 and 15 t ha^{-1} yr^{-1} of reed dry mass have been assumed for the subsequent commercial considerations.

Land use of reed compared to alternative sources of industrial raw materials and energy

Scale is an important factor if industrial processing is to be economically attractive. For instance, a minimum economic rate for pulp production is 150,000 t yr^{-1}, for ethanol 50,000 t yr^{-1}, for fibreboards 35,000 m^3 yr^{-1}, for electricity generation 30 MW and for pellet production 50,000 t yr^{-1}. The areas required to grow the necessary quantities of raw materials for these industries are depicted graphically in Figure 1, which shows that the area required for reed production is notably lower than that required for harvest residues (straw) but 1.5–2 times the area required for cultivated biomass (*Miscanthus*). On the other hand, the Indirect Land Use Change (ILUC) factor, which has consequences for GHG emissions, is zero (0) for reed and straw and practically unity (1) for both wood and *Miscanthus*.

Challenges of large-scale reed exploitation

Cutting and bundling the reed by hand on a large scale is successfully practiced in China. More generally, as reed grows in marshy areas, access to the reed beds for mechanised harvesting and transport can be problematical and costly, especially in places where there is no seasonal period of low water or ice in winter. Several solutions are being developed for such conditions: in central and eastern Europe amphibious harvesting machinery has been

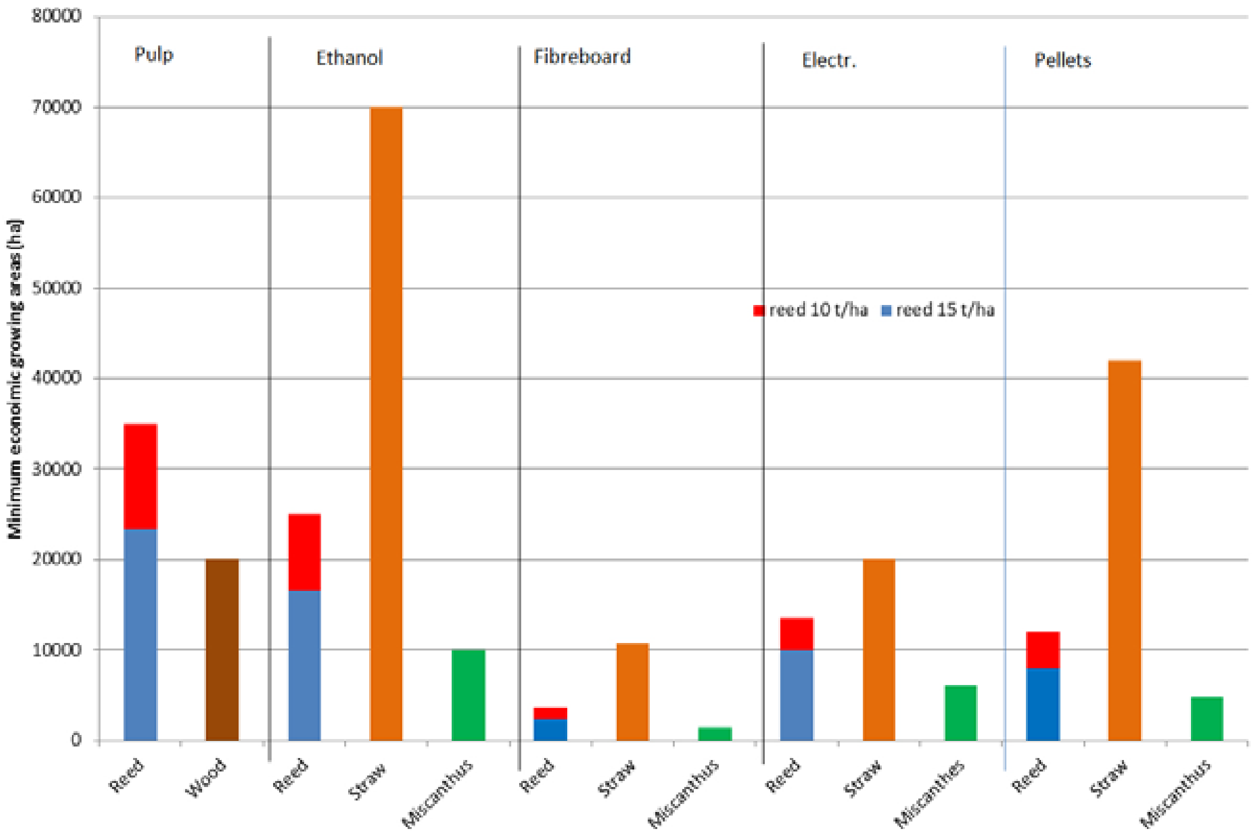

Figure 1. Minimum area (ha) required for commercial production of various products using reed, wood, straw or cultivated *Miscanthus* as feedstock. Based on the following average yields (t ha^{-1}): wood (eucalyptus) 20, *Miscanthus* 25, rice and wheat straw 3.5, reed 10 and 15.

developed (Alsbury 2010) and in The Netherlands harvesting machinery with low ground pressure that is capable of working in inundated areas is used (personal communication Hanze Wetlands and De Vries Cornjum). Developing such machinery is the main challenge for the exploitation of reed.

CONDITIONS AND FACTORS FOR SUCCESS IN COMMERCIAL REED EXPLOITATION

The commercial exploitation of reed is attractive for the industrial sector if the following conditions are met.

- According to industry and financiers, the return on investment in processing plant is at least around 20 % yr^{-1} (payback period no more than five years).
- A secure quantity of the reed is available to supply an economically sized processing plant operating year-round.
- It is desirable that the supply of the reed is spread over the year, so that the need for storage space is minimised.
- The supply of raw material (reed) is guaranteed for a period that is significantly longer than the amortisation period of the investment in the processing plant (thus preferably > 5 yr).
- The price of the reed delivered to the plant is, and can be expected to remain, competitive with alternative biomass sources.

In many countries subsidies, carbon credits and tax facilities in various forms are available for the use of renewable resources, but most industries are also subject to taxation. Changes in these incentives and disincentives (GSI 2008) can alter investment decisions. However, as taxes and subsidies differ by country and change over time, they are too complex for discussion in this article.

In the following paragraphs I elaborate the conditions and success factors for the commercial uses of reed for which suitable commercial scale proven (or almost proven) technologies exist such as pulp, energy, bio-ethanol and fibreboard production.

REED AS RAW MATERIAL FOR PULP PRODUCTION

In 2003, the worldwide demand for papermaking fibres was expected to rise from 350 to 450 Mt yr^{-1} by 2015 (Croon & de Man 2007). Although this predicted growth has been tempered by the current economic crisis, the demand for fresh fibre for pulp can be expected to continue rising because of the continued rise of paper consumption in Asian countries.

Paper can be produced from wood or non-wood pulp. The main raw materials for wood pulp are hardwood and softwood chips of which 2–2.5 t are required to make 1 t of pulp. The rising demand before 2008 prompted widespread planting of trees for pulpwood production. Although less publicised, in some countries (e.g. Brazil) this resulted in the conversion of areas where food crops were grown to pulpwood production. Traditionally, prices of woodchips ranged from 25 to 50 \$(US) t^{-1} (metric tons). Recently, prices of up to 70–75 \$ t^{-1} have been quoted. Expectations are that the future world demand for pulp cannot be satisfied by wood chips alone and that non-wood pulp production must be increased.

Reed-based (non-wood) pulp is not new: it has been produced for centuries in China, which at present produces 10 million t yr^{-1}; and non-wood pulp amounts to 25 % of the total pulp production in India (Powlson 2011). The traditional technology for the production of non-wood pulp (China) is highly polluting and an expansion thereof is not desirable. New non-polluting technologies for non-wood pulp production have been developed over recent decades. Examples are the Free Fiber technology (Metso GMBH), the Conox technology (Conox Ltd) and the Chempolis technology (Chempolis Ltd). For all of these technologies it is claimed that pollution from non-wood pulping processes is within modern acceptable norms (Croon & de Man 2007).

The qualities of reed (*Phragmites australis*) as a raw material for non-wood pulp are not in doubt. The qualities of *Phragmites* pulp are similar to, and in some respects surpass, those of eucalyptus pulp, which it can replace for all applications (Ververis *et al*. 2004, Croon 2004, Lips 2007). The industry claims that, for the production of 1 t of pulp, around 2.4 t of dry reed are required (Chivu 1968).

Bamboo is often seen as a ‘green’ alternative raw material for pulp production and large-scale pulp mills based on bamboo have been built, for example by the Guizhou Chitianhua Paper Industrial Company Ltd., China. This is not without controversy since large-scale harvesting may threaten the many ecosystems where bamboo grows.

The commercial attractiveness of a modern non-polluting non-wood pulp mill is determined by its scale, availability of the feedstock reed at reasonable prices and the market price of pulp. More specifically:

- The minimum economically viable modern non-wood (reed) pulp mill has a production capacity of 300,000 t yr^{-1} according to most technology suppliers. A pulp mill producing 150,000 t yr^{-1} might be economically acceptable in special conditions. The investment required for a 150,000 t yr^{-1} pulp mill is in the order of 1,600 \$ t^{-1} yr^{-1} capacity or around 250 M\$ in total.

- The feedstock requirement for a 150,000 t yr^{-1} reed-based pulp mill is around 350,000 t yr^{-1}. To limit costs for transporting bulky reed bundles (bulk density about 0.125 t m^{-3} *vs.* about 0.8 t m^{-3} for woodchips), the pulp plant must be located within 25–30 km of a reed producing area of 25,000–35,000 ha. If the reed is compacted in the field and transported as bales, these must be taken apart again at the processing plant.
- Pulp prices vary a lot in time and with quality. In 2005, prices were 610 \$ t^{-1} for long-fibre and 450 \$ t^{-1} for short-fibre pulp (UPM-Kymmene 2005). If prices are around 450 \$ t^{-1} a return on investment of around 15 % can be obtained only with unrealistically low reed costs of 30–35 \$ t^{-1}. If the price of pulp is 700 \$ t^{-1} (price at October 2012 in the USA) a reasonable reed price of 70 \$ t^{-1} can be supported to obtain a return on investment of around 15 % (Croon & de Man 2007). Although the range of return on investments is on the low side by normal industrial standards, it seems acceptable when compared with the returns from established paper mills. Thus, in present economic conditions, reed can be a commercially attractive feedstock for non-wood pulp production if a concentrated reed growing area of 25,000–35,000 ha is available and the cost of the reed delivered at the gate of the mill is no more than 70 \$ t^{-1}. A return on investment of 15 % is seen as acceptable for the pulp industry.

REED AS A SOURCE OF THERMAL ENERGY

The potential of reed as a renewable energy source results from its relatively high calorific value of around 17–18 MJ kg^{-1}, which is similar to that of wood (about 20 MJ kg^{-1}) and about half that of the coal feed of power stations (25–33 MJ kg^{-1}). The availability of reed in large quantities can contribute to the worldwide rising demand for renewable energy (Ash 2009, Deutmeyer 2012).

Reed can be burned directly to produce heat, but it is more effective to chip or mill the reed to powder before burning. In practice it is even better to transform the reed into denser energy carriers such as briquettes or pellets. The resulting energy carriers can be used for direct combustion or they can be converted into bio-coal or syn-gas (synthesis gas, containing mostly hydrogen and carbon monoxide). The most common use to date is direct combustion of briquettes or pellets or, to a lesser extent, gasification.

In comparison with most other biomass fuels, a disadvantage of reed as a biofuel is its relatively high ash content of 3–7 % compared with 1–2.2 % for wood (ECN 2012, Dr V. Aurich personal communication). This means that modifications of the furnaces to handle larger ash quantities are required, but because the melting temperature of reed ash is rather high (canary grass 1,100 ºC) it does not interfere with the combustion of coal in the furnace.

Direct combustion of air-dry reed (15–20 % moisture), briquettes or pellets alone or in combination with coal (co-firing) is possible in power generation plants *via* standard steam cycles where electricity is produced and waste heat remains. Chopped and powdered reed can, for practical reasons, be used only in specialised and, up to now, small-scale installations. Pellets and briquettes are used for home heating and, increasingly in Europe and the USA, for domestic fireplaces.

The commercial viability of electricity generation using reed as feedstock is determined by the capacity of the plant, the investment required, the cost of the reed compared with alternative energy sources like coal and the value of the electricity generated. Some basic figures follow.

- Plant capacity: economies of scale are important. As an example, a 30 MW biomass-based electricity plant that has been recently constructed with a designed efficiency of 25 % (the maximum efficiency of large-scale plants is around 50 %; Ir. K. Gorter personal communication 2006). The resulting power generated is 180,000 MWh yr^{-1} which requires a supply of about 150,000 t yr^{-1} of chopped reed grown on an area of 10,000–15,000 ha. Larger plants with higher efficiency (35 %) will be commercially more attractive.
- Investment is around 1.5 M\$ (MWh)$^{-1}$ capacity and operation costs are about 4.5 \$ MW^{-1}.

A business case calculation showed that, if the selling price of electricity is about 0.13 \$ kWh^{-1} and the reed costs 70 \$ t^{-1}, the return on capital is 20 % and the payback period is 5 years.

The direct use of untransformed dried reed, with a density of 0.125 t m^{-3} or less, can theoretically be considered for point of use power generation. If the reed has to be transported over larger distances, the reed has to be compressed into either briquettes (0.3 t m^{-3}) or pellets (1 t m^{-3} or bulk density 0.7 t m^{-3}) for easier handling and lower transport cost.

Many power stations are already equipped to co-fire their generators with wood pellets, for which there is a world market. According to industry sources reed pellets are commercially interesting only if they are delivered at regular intervals in batches of at least 10,000 t with a minimum annual total of 60,000 t, for which a reed growing area of 4,000–6,000 ha is required.

Pelleting techniques for wood-based biomass have been fully developed in Sweden, where the average plant capacity is 40,000 t yr^{-1}. Pelletising and briquetting techniques have been specifically developed for reed, though on a small scale, for the Ukraine (Fieldfare 2000, Kronberg & Kronberg 2011). Small-scale pellet production requires investments ranging from 50,000 to 100,000 $ (ton hr)$^{-1}$ capacity. With a reed price of 70 $ t^{-1} and processing costs in the order of 45 $ t^{-1} (based on data from the industry), a rate of return of 20 % can be achieved if the sales price of pellets at the plant gate is between 100 and 140 $ t^{-1}. Current market prices for pellets are around 140 $ t^{-1} (CIF, Cost Insurance Freight Europe, personal communication European power generators). Profitability is sensitive to the cost of the reed delivered to the plant and, probably, to the scale of the operation.

Transforming reed into Syn-gas through controlled partial combustion (mostly carbon monoxide and hydrogen) is another option. Syn-gas can potentially contain up to 80 % of the energy contained in the biomass supplied. Syn-gas is mostly used for further processing into green chemicals and seldom burned directly for energy generation. Many technologies are under development for the gasification of biomass, both small scale (biomass < 1 t day^{-1}) to very large scale (1,000–10,000 t day $^{-1}$) (E4tech-NNFCC 2009). Once the corresponding processes are developed and proven for large-scale commercial use of reed as feedstock, either directly or in pelletised form, viability will have to be assessed. Syn-gas is not, at present, a realistic commercial option without subsidies. Reed can be transformed into green charcoal, bio-coal or biochar through pyrolysis. Green charcoal can be used as a substitute for traditional wood charcoal, for co-firing in coal plants, and as a soil improvement product (biochar). This option has attracted wide attention. The traditional small-scale production of wood-based charcoal using a 'kiln' technique is inefficient and polluting. Several alternative technologies are under development. The most efficient is probably torrefaction (fluidised bed-based pyrolysis: heat treatment in the absence of oxygen at temperatures above 250 ºC) with an energy recovery of about 70 %. This process requires 1.0 t of dry reed to produce about 0.35 t of green charcoal (Deutmeyer 2012). Other development efforts concentrate on a retort process (fixed bed operation). Once green charcoal is accepted as a replacement for household (cooking) applications, it may become an important factor in the reduction of deforestation caused by traditional charcoal production. In a thesis, Mfouapon (2007) argued that small-scale 'green charcoal' production with improved technology using bulrush (*Typha*) is feasible under West African economic conditions. A more recent publication (Caro *et al.* 2011) cast doubt on the commercial feasibility at present because the acceptability, the marketing systems and the large-scale harvesting and processing methods all require further development, and the wholesale price is lower than assumed by Mfouapon (2007). Caro *et al.* (2011) also stress that large-scale production will provide the highest returns if the technology is fully developed for large-scale production: scale will be decisive for commercial viability.

For large-scale torrefaction of wood and other biomass (including reed) into charcoal, no specific data are available regarding projected investment and production cost (Anonymous 2012b, Deutmeyer 2012). Indications of cost and benefits are available for only small-scale units as given above. Any extrapolation to large operations will require a 'modular' scale-up (multiple sets of equipment) and will not include economies of scale.

Thus, although the market potential of green charcoal is recognised as a major technological opportunity, effort is still needed to make large-scale production profitable.

In summary, reed as a renewable energy source can potentially be useful for power generation in co-firing applications. This holds especially in the European Union where power companies are required to replace up to 10 % or more of their coal consumption with renewable resources. The additional ash load produced by reed can technically be coped with, at a cost.

Electricity generators have a strong preference for reed supplied in a pelleted form with the highest possible bulk density. Once the cost of pellets (production and transport) is competitive, large-scale sales are possible. This, in turn, facilitates the building of commercially attractive large-scale pellet production plants. Such reed pelleting operations have great potential.

Advanced technologies for gasification and torrefaction are still under development. When mature, they will produce a higher-value product than pellets or briquettes. Commercially interesting opportunities depend on the market energy price and the price of the dry reed delivered at the plant. For a price ≤ 70 \$ t^{-1} for reed, business options are available, particularly because other reliable biomass supplies are becoming scarce and energy is getting more expensive.

REED AS A RAW MATERIAL FOR SECOND GENERATION BIOETHANOL PRODUCTION

There is a large and increasing world market for fuel grade bioethanol, a liquid renewable fuel. Prices (without subsidies and taxes) fluctuate around 1,040 \$ t^{-1} (800 € t^{-1}). In Europe, prices can rise seasonally to 1,300 \$ t^{-1} (1,000 € t^{-1}) (personal communication from Ethanol dealers and Bloomberg). According to the International Energy Association (IEA), worldwide consumption is expected to rise from 50 Mt yr^{-1} in 2010 to 250 Mt yr^{-1} in 2030 (IEA 2007).

Fuel grade bioethanol can be made from sugars, starches and celluloses. At present 75 % of fuel ethanol is produced from the sugars and starches (first generation) in sugar cane, maize and wheat (IEA 2007). The use of these crops for energy is controversial and gives rise to ‘food crops *versus* energy crops’ discussions. Second generation bioethanol produced from cellulosic substances such as harvest and forest residues (straw, branches), reeds and wood is non-controversial. The International Energy Association expects that 125 Mt yr^{-1} (50 %) of bioethanol will be produced from cellulosic materials by 2030 (IEA 2007). Thus, it can be anticipated that the demand for cellulosic feedstock will increase and that prices will rise. Reed is suitable for the production of bioethanol. The ligno-celluloses of reed (35–50 % of dry mass) can be converted by enzymatic hydrolysis into sugars and lignin. The sugars can then be fermented by yeast into alcohol and subsequently distilled into fuel grade ethanol. According to the Chemtex Company of Italy, the lignin (10–25 %), a by-product of the process, has an energy content of around 20 MJ kg^{-1} and can be used to generate electricity and steam, so that the ethanol plant is self-sufficient in energy with around 20 % surplus that can be sold to the grid.

The technology of converting biomass such as reed into ethanol on an industrial scale has recently come out of the pilot phase. Important hurdles in developing the conversion technology on an industrial scale which are claimed already to be cleared are: pre-treatment of the biomass, the efficiency of the enzymes for hydrolysing, and of selection of the yeast for the fermentation. Other technologies based on gasification have also been developed. After many trials and pilots three industrial-scale plants (one in Europe and two in the USA) with a production capacity of about 50,000 t yr^{-1} are under construction and will start operating in 2013/2014. Maize stover (leaves and stalks left after the cobs are harvested) will be the feedstock in the USA and giant reed (*Arundo donax*) and straw will be used in the European plant. According to the publicity of Chemtex Inc. in 2011 and INEOS-bio Inc. in 2013, 3–5 t of reed will be required to produce 1 t of fuel-grade bioethanol. The scale, availability and cost of the feedstock delivered to the plant, and the sale price of the ethanol produced, will determine the commercial viability of a reed-to-bioethanol conversion plant.

As far as scale is concerned, most technology suppliers claim that the minimum economic size of a plant is 50,000 t yr^{-1} for which 200,000–250,000 t yr^{-1} of reed is required. Investment in such a plant is estimated in Chemtex Inc. publications to be around 4,000 \$ t^{-1} yr^{-1} capacity. This includes the electricity and steam generation unit, which will burn lignin, and a wastewater treatment/recycling unit. The processing costs of such plants are around 250 \$ t^{-1} of ethanol.

Based on a reed price of 70 \$ t^{-1} and a sales price of the fuel grade ethanol of 1,050 \$ t^{-1}, the return on investment (without subsidies and taxes) is around 20 % yr^{-1} and the payback period is about 5 years. If the subsidies and tax allowances which are available in many countries are taken into account, the return on investment quickly rises to over 25 % yr^{-1}. Profitability for the reed producers is location-dependent and highly sensitive to reed yield (t ha^{-1}) and harvesting costs. A net annual income of 320 \$ ha^{-1} yr^{-1} without subsidies and 800 \$ ha^{-1} yr^{-1} with subsidies was calculated for a reed yield of 10 t ha^{-1} and a selling price of 70 \$ t^{-1} (based on a confidential study on the costs of reed harvesting and transport).

Reed has potential advantages over alternative raw materials. Besides sugarcane, wheat and maize which are mainly used as first generation feedstock, starch-containing crops such as cassava, sorghum, sweet potatoes and potatoes grown on marginal soils are often considered as non-controversial alternatives. These crops are also food crops which could eventually become part of the food *versus* energy controversies. High yields and efficient cultivation methods are required to produce such feedstocks at acceptable costs in the required quantities from a limited area. On marginal soils particularly, this requires substantial investments in soil improvement and infrastructure, and may also require irrigation with scarce fresh water.

Alternative second generation bioethanol feedstocks are cultivated cellulosic crops such as *Arundo donax* and *Miscanthus*, which can reach yields in the range 25–40 t ha^{-1}. To obtain such high yields these crops would also require infrastructure investment, and would potentially compete with food crops for land and water. Recently, a large project for a 1.3 Mt yr^{-1} ethanol plant in the USA was stopped because the cost of the feedstock was greater than anticipated (Bulls 2012).

Harvest residues such as straw and forestry residues are available in huge quantities and seemingly have zero ILUC values. It can be argued that exporting harvest residues from agricultural fields means ‘export of (physical and chemical) fertility’. How serious this is depends on the local soil conditions. The general experience so far is that the cost of collection, compaction and transport (for which the US government pays a subsidy of 50 \$ t^{-1}) of the required quantities of biomass, which is spread over large areas, can be prohibitive (ECCEC 2010).

The areas required to supply a 50,000 t yr^{-1} bioethanol plant with various kinds of feedstock, based on average yields, are shown in Figure 2.

The area required to produce reed is in the same order as that for wheat and maize, but the area required for residues is much larger. The ILUC factor for reed and residues is zero because naturally growing reed does not cause land use change and straw is a secondary product of a food crop. Cultivated crops (*Miscanthus*, *Arundo donax*, maize, wheat and sugarcane) have ILUC factors of about 1. It can thus be concluded that reed is a commercially attractive feedstock for the production of renewable fuel-grade bioethanol. Reed scores better in all aspects than alternative first generation and biomass feedstocks, does not compete with food crops for land and water, and causes no land use change.

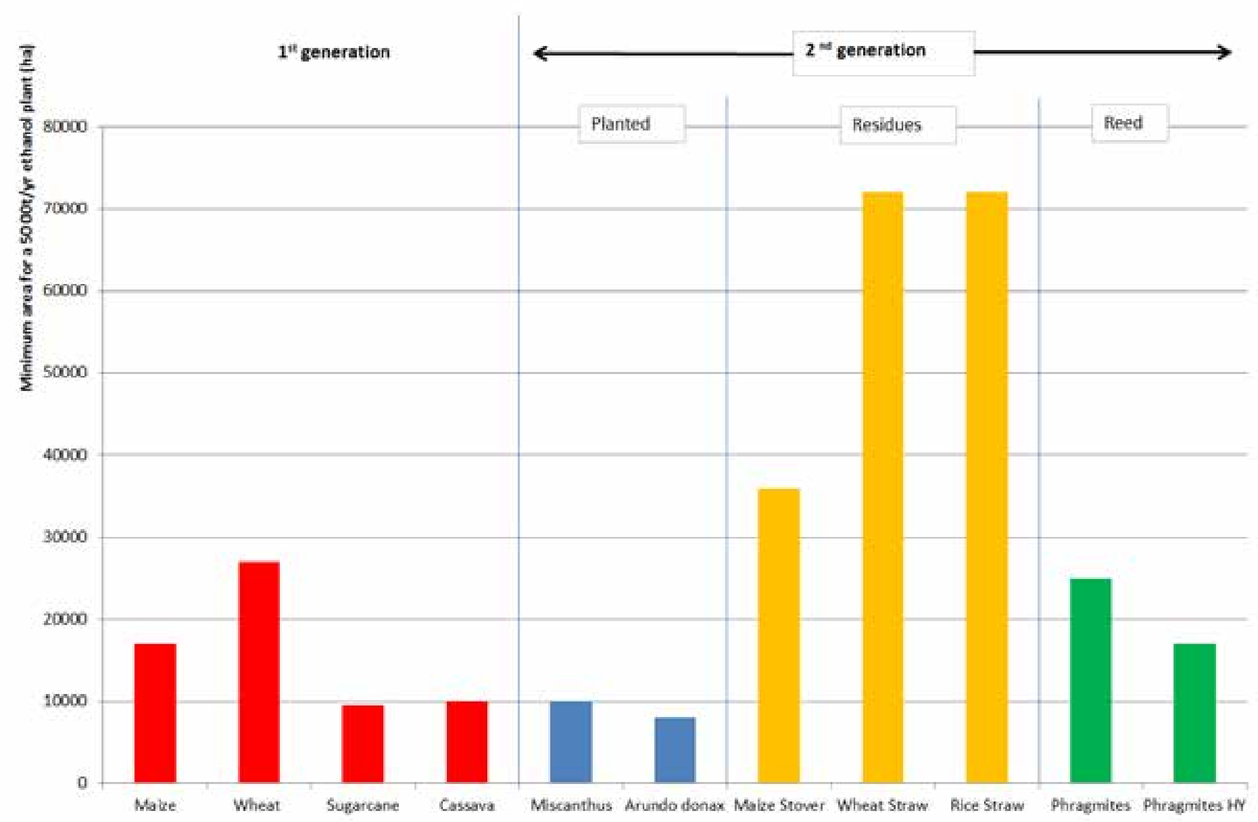

Figure 2. Minimum area (ha) required for the production of feedstock for a 50,000 t yr^{-1} bioethanol plant. Using average yields (t ha^{-1}) partly based on FAO data and USDA information: maize 8, wheat 5, sugarcane 75, cassava 15, *Miscanthus* 25, maize stover 7, rice and wheat straw 3.5, *Phragmites* (reed) 10 and *Phragmites* HY(high yield) 15.

REED AS A RAW MATERIAL FOR THE PRODUCTION OF FIBREBOARD

Fibreboard is taken as an example for the potential large-scale use of reed for the production of building materials**.** Fibreboards are multi-layer boards that are mainly made of wood fragments and wheat straw bonded with a resin. Fibreboard has many uses in the building and furniture industries. The long strong fibres of many reed species make them suitable, and arguably preferable to straw, for the production of fibreboard. Worldwide production of fibreboard in 2005 was quoted to be around 35 Mm³ of which a large part was produced in the USA and Canada. Since 2005 new plants have started up in Europe and Asia (China). Taking into account increasing urbanisation, it is expected that demand will be strong and growing. Wholesale prices range from 250 to 450 \$ m^{-3} depending on market conditions and quality.

The minimum scale of a commercially interesting fibreboard production unit is 35,000 m³ yr^{-1} for which about 36,000 t of dry reed, harvestable from about 3,600 ha, are required. The investment in a plant is 15–25 M\$ and the production costs vary with the costs of energy and of the resin used to bind the fibres which accounts for 3–5 % of the weight of the end product, costs (in 2013) about 2500 \$ t^{-1} and amounts to around 150 \$ m^{-3}. Larger plants will be more economical as the fixed costs are > 20 % of the production costs (Croon 2004, updated for technology change and inflation). Based on a reed price of 70 \$ t^{-1} the return on investment ranges between 15 % (if the sale price of boards is 250 \$ m^{-3}) and 25 % (if the sale price is 350 \$ m^{-3}). Payback periods are 4–6 yr.

Thus, reed can become an environmentally and commercially interesting raw material for the production of fibreboard.

DISCUSSION

It can be concluded that the reed that grows naturally on all continents can serve as a technically suitable and commercially interesting source of renewable energy, either as a fuel for direct incineration or as a raw material for bioethanol or charcoal replacements, as well as for pulp and building materials. It is even possible that reed may be a source of textiles, but too little is known about that at present. The exploitation of reed does not compete with the production of food crops, either directly or indirectly (by using scarce cultivable land and scarce fresh water resources).

If reed is used as a raw material for the industrial uses considered in this article, naturally growing reed acquires an economic value, which will provide a strong incentive to maintain and protect the reed lands that often double as nature areas and serve as natural protection against erosion and pollution.

Some of the technologies for the processing of reed (pulp, ethanol, fibreboard, pellets and direct combustion) are well known and mature; others are on the brink of becoming useful. The main impediments to exploiting reed are the cost of reed delivered to a processing plant and the fact that commercially successful operation is feasible only on a large scale. Investment in a processing plant is expensive. The large commercial risks require a reliable reed supply.

The cost of reed supplied to a processing plant is almost completely determined by the costs of transport and harvesting. To limit the transport cost of this bulky raw material, the processing plants are best placed close to, or preferably in the middle of, the reed production zone. Large concentrated reed production areas, such as those that occur in some deltas, have a commercial advantage. The cost of harvesting and transport is partly influenced by the yield: the larger the yield the lower the cost. Major benefits can thus be obtained by increasing yields and by developing systems for efficient large-scale harvesting, and for bundling, chipping or baling the reed where it grows.

Present yields of reed are estimated to average 10–15 t ha^{-1} yr^{-1}. According to field observations and information from reed growers, yields can be increased relatively easily by either or both varietal selection and minor improvements to the growing conditions.

Efficient large-scale harvesting techniques, which are site-specific, have still to be optimised for those areas where manual harvesting is not a realistic option. These techniques may have to be developed in conjunction with improvements to infrastructure.

Despite the attention to be given to harvesting and transport techniques, the exploitation of naturally growing reed is much simpler and cheaper than the cultivation of conventional crops. No soil cultivation and irrigation, and little or no fertiliser and pesticide are required. Neither are extensive and costly infrastructure improvements and organisation usually required.

The scale requirements translate into the need for large single areas where reed can be harvested. The area required to produce the commercially required volumes of reed is smaller than for harvest and forest residues (Figure 1), but larger (double or more) than that needed for cultivated crops (*Miscanthus* or wood). On the other hand the ILUC factor is practically zero for reed which has, in addition, commercial and environmental advantages.

I have calculated a preliminary estimate of the commercial consequences of using reed as a raw material for different purposes, based on indicative costs and current scale factors (Table 1), using indications from the industry and from market reports. The average yields are based on previously quoted data. This Table shows that, with the exception of small-scale charcoal production, reed is potentially a commercially attractive raw material, provided that the cost of dry reed delivered to the site is not more than 70 $ t^{-1}. Providing value to reed through its commercial exploitation will have many positive benefits and will contribute to the universal wish to develop renewable resources. To realise this it is necessary to create for the relevant industrial players, technology providers (and possibly governments) an awareness of the existence, availability, qualities and commercial attractiveness of reed and its advantages over other renewable resources. Once such awareness is created, it can be expected that support and input from governments, industry and technology providers will become available for further optimising reed production and, where necessary, processing technology.

Steps to be taken for creating awareness and the subsequent exploitation of reed can be summarised as:

- Preparation of a comprehensive inventory of the naturally available reed species, their yield potential and growing conditions, with emphasis on their salt tolerance.
- Preparation of a world inventory of the large reed growing areas with, where possible, specifications of the prevalent species and potential yields.
- The initiation of applied research to increase reed yields.
- Further development of cost-effective harvesting methods, including machinery and appliances for large-scale applications.
- Either or both further development and optimisation of the technologies for the conversion of reed into fuel (pellets, briquettes, bio-coal, and charcoal replacements) or bioethanol, building materials and possibly textiles.

Table 1: Summary of commercial aspects of using reed as a raw material for products and energy.

ITEM	**UNITS**	**PRODUCTS**			**ENERGY**		
		Pulp	**Ethanol**	**Fibre-board**	**Pellets**	**Electricity**	**Charcoal**
Cost input of reed	$ t^{-1}	70	70	70	70	70	70
Market value ex plant	$ t^{-1}	600	1,040	310	110	130 $(MWe)^{-1}$	*225*
Minimum capacity	t yr^{-1}	150,000	50,000	38,000	*60,000*	30 MWe	3,000
Reed required	t yr^{-1}	350,000	250,000	35,000	*60,000*	150,000	9,000
Area of reed:							
for yield 10 t ha^{-1}	ha	35,000	25,000	5,750	6,000	13,500	900
for yield 15 t ha^{-1}	ha	25,000	17,000	3,800	4,000	10,000	600
Investment:							
per ton y^{-1} capacity	$	1,600	3,000	675	100–200	1.5 M$ MW^{-1}	250
total for min. capacity	M$	250	200	25	6–12	45	0.75
Production cost	$ t^{-1}	90	250	215	45	13 $(MWe)^{-1}$	20
Return on capital	%	15	20–25	20–25	20	20	*20*

All data used are general estimates, which may vary considerably from case to case.
Italic: data unlikely to be realistic under present conditions.

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