Technology Review Report
for
AHDB Cereals

Carried out by

NFU Energy
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Contents

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Background

The GrowSave programme's Cereals Sector aims to identify and publicise the latest technologies that can help cereal farmers to improve their efficiency, specifically in the realm of energy efficiency, but also to highlight and promote climate or environmental improvement actions.

Most energy consumption for fixed equipment in the Cereals Sector is that needed for grain drying, cooling, and storage, with heat being the largest energy use. Therefore, any technology improvement or increase in process efficiency can have a large effect on the overall energy use in the sector.

Discussions with AHDB Cereals team on the information available, regarding energy consumption and efficiency, highlighted a perceived gap in knowledge and a lack of up to date material. This review was commissioned to investigate whether that perception is real and where the requirements lay for further work to upskill and update the sector.

Set against a desire by consumers and processors to achieve reduced carbon emissions, this technology review, coming at the outset of the GrowSave cereals programme, aims to bind the Knowledge Exchange work for the coming years.

The discussions in this document arise from relevance to the sector, as highlighted by participants in this review.

Brief

- To assess the quantity and quality of available information in regards energy use and efficiencies in the sector
- To determine the potential for improvements in energy consuming areas in the Cereals Sector.
- To identify emerging technologies in the Cereals Sector.
- To put forward those recommended for implementation.
- To qualify key areas for more detailed work in GrowSave.

Methodology and references

Following a methodology as agreed by the Cereals Sector Steering Group and taking a similar approach to the AHDB Pork and AHDB Dairy Sectors Technology Reviews, several key areas were identified. Outline research and investigation was conducted to determine their relevance and potential. This was by:

- AHDB sector lead conversation
- Discussion with Industry figures
- Prior NFU Energy knowledge and work
- Internet and other research media

This report summarises the outcomes of these conversations and provides detail of the technologies discussed alongside a review of information and resources currently available.

The review can be broadly split into three categories:

- Existing literature and resources
- Grain drying theory and common technology
- Energy consumption, generation and efficient use

Energy consumption requirement in the cereals sector

After harvest, grains and oilseeds go through the following stages before leaving the farm or being used:

- Moisture testing
- Grain Drying (If necessary)
- Storage

Depending on the weather and ambient conditions, the length and energy use of processing grain on the farm can change drastically. The most extreme of these, in terms of energy use, is the grain drying process, which can span between several days and several weeks in any given year. Clearly, the length of drying season has a direct effect on the consumption of energy that, for a 'wet year', can be significantly higher than for a 'dry year'. Inherent variability also exists between parts of the UK as weather and harvesting conditions are localised. This variability in drying season presents a potential barrier to development, since there is not a guarantee for full use of a new asset, and therefore high variability in return on investments.

Why grain is dried

Once harvested, grain is still biologically active and therefore continues to respire once in storage. Respiring grain gives off both heat and moisture; the ideal conditions for storage are those which keep respiration to a minimum but delivers the specification required for the market.

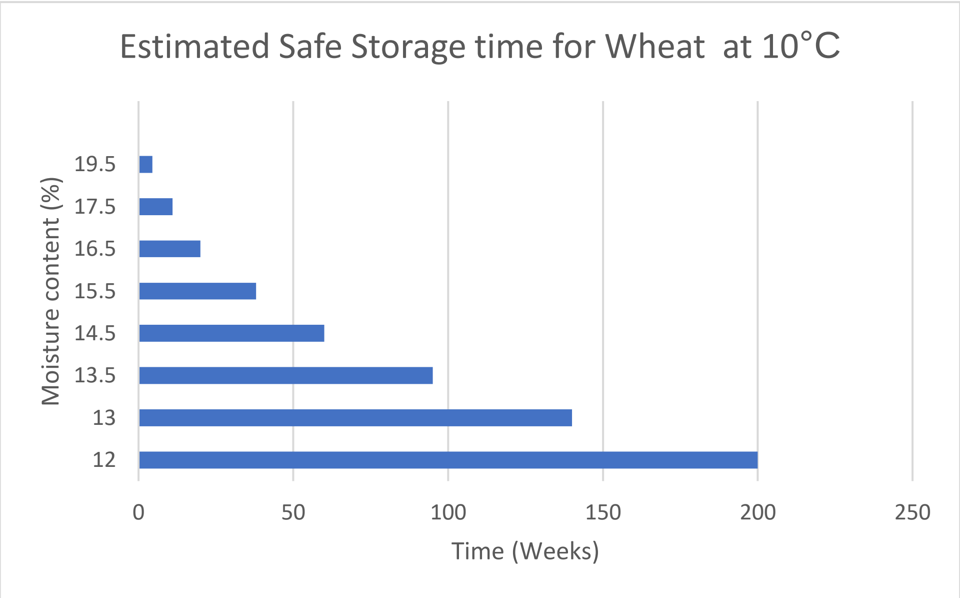

Figure 1: Data source: ADAS

Heat produced by respiration can lead to the development of hot spots in the grain mass. The higher the moisture content and the temperature of grain on delivery to the store, the greater the risk of hot spots. A vicious circle can be established of heating leading to greater biological activity resulting in the release of yet more heat causing increased temperature which in turn stimulates greater activity and so on. The released moisture from the heating grain can migrate upwards through the mass and condense in the cooler topmost layers. This can sometimes result in ideal conditions for growth and visible sprouting of the grain.

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The conditions outlined here can lead to partial or complete loss of the stored grain. In fact, most mills will have specific quality requirements for grain; these include but are not limited to:

- Nitrogen content (a measure of protein content),
- Hagberg falling number (a measure of enzyme activity),
- Admixture (impurities such as other grains, chaff and dirt),
- Mycotoxins (poisonous compounds resulting from fungal activity),
- Pests, such as weevils, and moisture content.

Failure to meet the spec on any of these counts will result in financial surcharges or even rejection at the mill gate for an out of spec product. Out of spec conditions also increase the risk of pests in stored grain.

Drying grain before storage can therefore serve to minimise the risk of long-term spoilage and will also act to condition and clean grain.

Apart from ensuring the highest quality product, it is often the case that as time goes on, the price for grain will increase following the decrease in availability, meaning that lengthening the storage life can result in direct financial benefit. Additionally, the ability to dry grain extends the harvest season, allowing larger acreages to be cropped by relatively small business.

Principles of grain drying

Approaches to drying grain can be broadly split into two categories: ambient and heated air drying. All methods rely on the same basic principle of drier air being passed through the wetter grain to absorb and carry away moisture. Ambient air systems will force unheated air through the grain to dry it and are generally thought to be more suitable for Eastern-UK counties, which generally see less rainfall than Western-UK counties. Ambient air systems will require greater energy consumption for the fans, since a greater volume of air will be required to remove moisture from the grain compared to a heated air system. Conversely heated grain drying will apply energy from fuels, unused in ambient systems. Therefore, a balance has to be created and appropriate system chosen that delivers the right drying effect for minimum cost, energy consumption or carbon emissions.

Why is ambient humidity so important?

The drying effect, as described above, relies on air carrying away the moisture from the grain. Simply put, the air must act as a sponge to soak up the moisture on contact with the grain, and it is therefore true that the dryer the air the greater its capacity to attract moisture and the faster or better the drying effect.

In understanding moisture content of air, we need to be certain of terminology and interactions. Therefore, below are described some of the principal factors to understand. Whilst the concepts are simple, the fact that air's capacity to hold moisture varies with temperature makes this a complex area to understand.

Absolute humidity – this is a measure of how much water in grams there is in a kilogram of dry air, expressed in g/kg.

Saturated air – this is air that is at its capacity to hold water, and therefore cannot absorb additional water. It will often seek to give up some of this water, for example as rain or condensation.

Humidity deficit – also expressed in g/kg, this is the additional water that the air could hold by comparison of its absolute humidity against its saturated moisture content capacity. This is an important unit to understand when related to the temperature of the air at any given point as air can hold more water at higher temperatures than at lower temperatures.

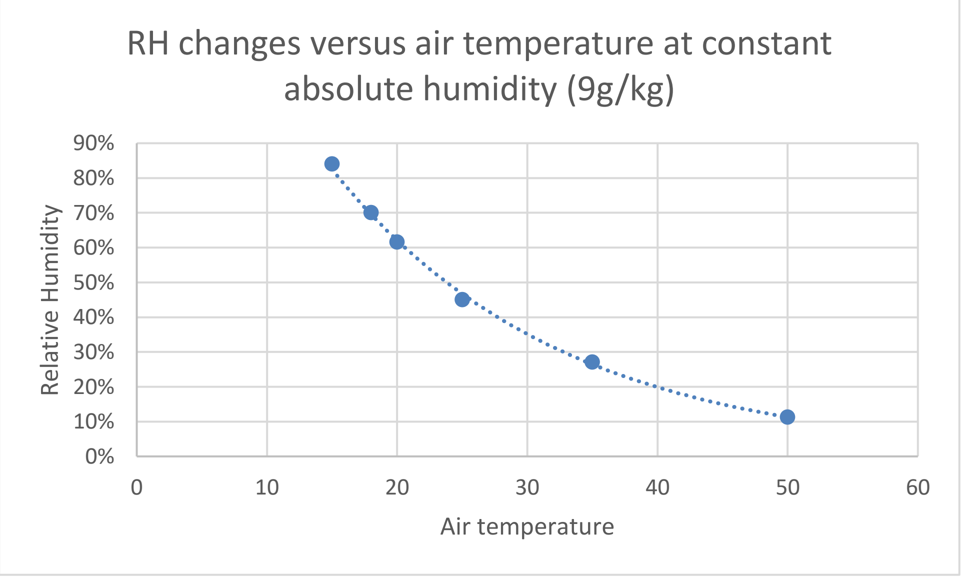
Relative Humidity – this is a ratio of absolute humidity to the saturated state, i.e. taking the actual quantity of water in the air and relating it to its total water holding capacity. Usually expressed in % terms, air at an RH of 80% will have the capacity to absorb moisture by an additional 20% of its capacity before it becomes fully saturated

Dewpoint – this is the temperature at which the air containing a certain quantity of water will be unable to continue to hold it and therefore must give up some of the water. When water condenses on a cold surface, the cold surface has forced the air to cool below its dewpoint for the water content it holds and therefore it released water.

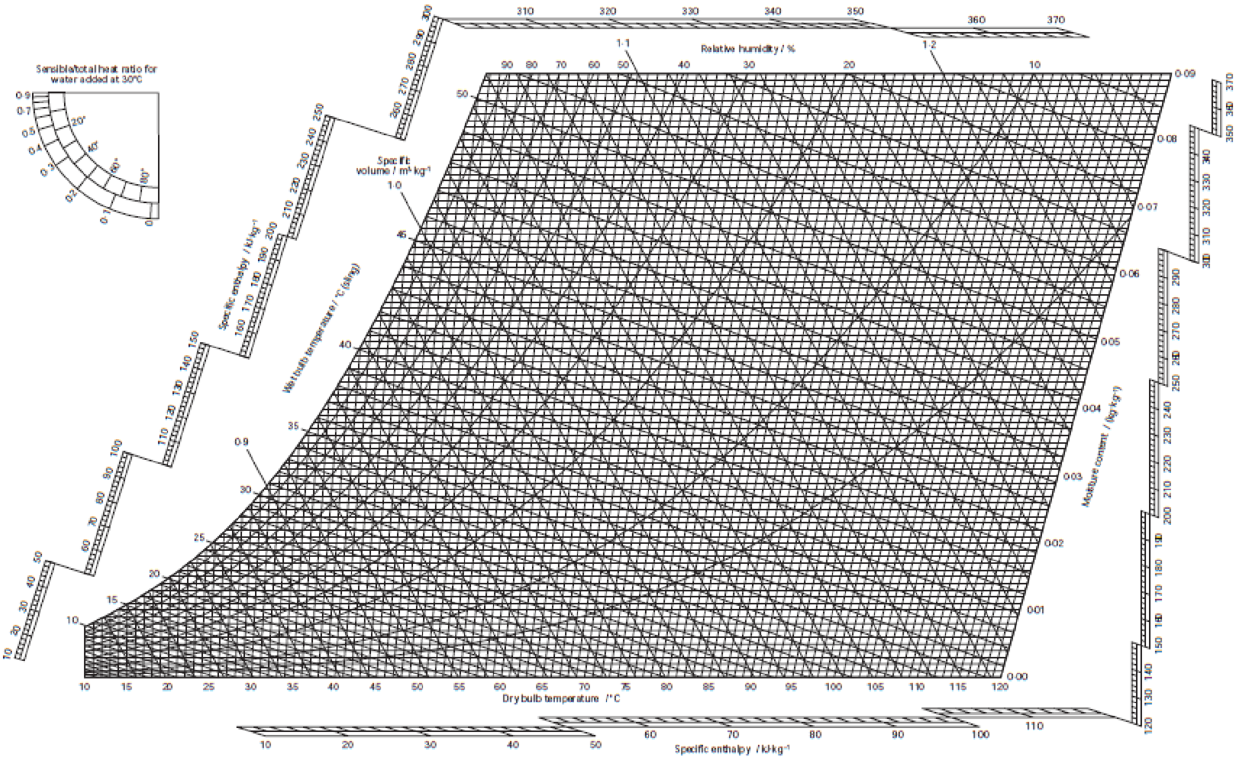
Vapour pressure deficit – measured in kPa, the mechanism by which water is transferred from a wetter material to a dryer one is termed vapour pressure; as water will want to move from a higher pressure to a lower one, the difference between the vapour pressure of the grain to that of the air is termed the vapour pressure deficit where a greater number demonstrates higher drying effect.

As discussed in the above definitions, the amount of moisture that air can absorb is determined by its temperature and the amount of water presently in the air can be described by its relative humidity (RH). As this is the most commonly used measure of humidity, we rely on expressions of RH to provide the drying capability of the air – air at 40% RH will be able to provide a greater drying effect than air at 80% RH, and air at 100% RH has no drying capacity at all.

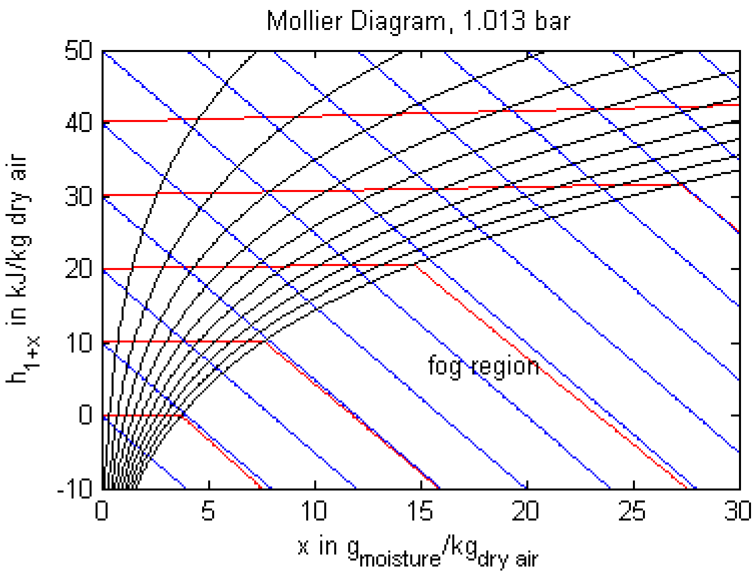
As air temperature increases, and with no additional moisture added then RH will fall, it is this principle that leads to the heating of air to improve and speed up drying. The chart below demonstrates the changes in RH as air temperature rises.



A full version of the properties of air is described by a Psychrometric Chart, or substituted by a Mollier diagram, which contains the same information presented differently. Both can be used to interrogate changes in conditions and their effect, an example provided in the image below and an interactive psychrometric diagram that can be interrogated online is at https://gpe.letsgrow.com/psychro



Reference – CIBSE Guide C 2007 – example of a Psycrometric Chart



Reference -
https://build.openmodelica.org/Documentation/Modelica.Media.Air.MoistAir.PsychrometricData.html

The role of dehumidification

Ventilating a crop with warmed air, with lowered RH, also tends to increase the temperature of the grain which further accelerates the release of moisture from the grain to the airstream. Within limits, the rate of drying can be increased by raising the air speed through the crop although this will increase the energy consumption of the system. Most farm installations are a compromise between speed of drying and energy efficiency.

The effect of raising temperature on the drying capacity of air explains the popularity of heating as part of the drying process. This is often a well understood technique, however it is also possible to improve the drying characteristics of air by removing its moisture (dehumidifying) and this can often be less energy intense than heating; although as dehumidification is electrically powered via a heat pump and heating is gas or oil the economics of both approaches need to be ascertained.

Not all dehumidification systems need to use a heat pump. Cool air passed through warm grain will exhibit decreases in relative humidity and consequent drying capacity (in the same way as does increasing the air temperature pre ventilation). This gives rise to a technique whereby the natural warming of the grain and warmth of the day can be used to effect dehumidification when passing cooler night time air through the grain. Reported to be used in north America as a technique, this is an approach contrary to many people's understanding and requires further exploration and explanation to determine the potential as an alternative in the UK.

Review outcome/ and recommendation

In preparing this report, many discussions were had with drying system operators and farmers. The level of knowledge on the principles of drying and how air contains moisture, the consequent effect of temperature and potential for dehumidification seems to require improvement.

We recommend a series of training courses/materials on the principles for relevant staff that will enable the right decisions to be made under differing drying conditions.

The energy requirement for grain drying is not well publicised; much of the literature references theory (which will be largely unchanged) but agricultural practice and technology efficiencies have moved on. Further work would benchmark the different drying approaches and carry out monitoring of several different grain drying systems to ascertain current practice and thus potential for efficiencies. This is a theme that covers the sections on technologies and energy efficiencies that follow.

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Grain drying technologies

For on farm grain drying, there are three main technologies typically employed in the UK: continuous flow, batch, and storage. All of which use one or more of a mixture of drying techniques previously described.

Continuous flow drier

Continuous flow driers offer rapid processing of large quantities of grain and use high temperature air to remove moisture from the grain in a very short period of time, air up to 100°C may be used, however this is carefully monitored and varies on the type of grain to ensure there is no damage caused.

Continuous flow driers move grain through a column, elevators discharge dry grain from the bottom and fill with wet grain at the top, the column remains full and the grain is continuously mobile. A fan is used to pull air through the moving grain via louvres in the column. The inlet manifold is split into two sections, air to the top section is heated to dry the grain and air through the bottom section is ambient to cool the grain.

Grain leaves the column at the correct moisture content and temperature for storage. The airflow through the moving grain also has the additional benefit of removing dust and chaff, further improving the sample.

Drying with this type of technology is an energy intense operation with even a relatively small 10t/h machine may be removing in the region of 800kg of water each hour. Continuous flow driers can be heavily automated, with the desired parameters set in the control system for a particular crop and desired specification.

On modern systems, adjustments can be made to grain flow rate, hot air temperature and fan speed. Heat can be supplied from a range of sources including biomass, however continuous flow driers in the UK are generally heated using either gas or oil to ensure the necessary high temperatures are reached. It is becoming more common with the proliferation of on farm biomass heating systems to find large water to air heat exchangers on the inlet to provide a base heat and reduce the load on the oil burners.

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Figure 2: A continuous flow grain dryer. Note, the central tower is the dryer, the side closest to the camera is the inlet manifold, the silo to the right of the dryer is for loading grain lorries and is not directly related to drying.

Batch drier

Batch driers tend to use medium temperature air and operate at a medium pace. The main principle of operation is that grain is loaded into the drier in batches and then remains within the machine potentially for several hours before being emptied once dry and cool; the drier can then be re-filled with the next batch of wet grain.

Batch drying machinery tends to consist of a one perforated cylinder within another, the space between the cylinders is filled with wet grain, a fan forces warm air into the central chamber which then passes through the perforations, through the grain, and exhausts through the perforations in the wall of the larger cylinder carrying moisture away with it. Stirrers or augers are used to keep the grain moving or re-circulating to avoid hotspots.

Once the grain has dried to the desired temperature, the batch drier repeats the process with ambient air to cool the grain back to a temperature safe for storing.

Historically, batch dryers were often mobile and may even have been powered by a tractor PTO, however modern systems tend to be static and electrically powered. Larger static batch systems found on modern farms have allowed elevators to be installed to fill and empty the machine, this has both allowed for greater automation of the control system and removed the requirement to load the drier manually.

Traditionally, batch driers have utilised medium temperature hot air, maybe up to 40°C, this opens up opportunities to utilise heat from various sources; biomass hot water systems and heat pumps are able to supply the 10-15°C temperature uplift required and are occasionally encountered. The ever-increasing scale and capacity of farm machinery has affected batch driers and many systems utilise oil fired heat to achieve higher temperatures, faster drying times and consequently greater throughput. As with continuous flow drying systems, a combination of alternative heat sources combined with an oil burner are found.

Figure 3: A pair of batch dryers in situ. Note that although these models are portable, here they have been installed permanently with augers to empty and fill the dryers, they have also been modified with hot water to air heat exchangers to supplement the heat supplied by the conventional oil burners.

Storage drying

With this technology, grain is dried in the same space as it will be stored and is generally achieved by blowing large volumes of air through the full depth of the crop from underneath. In the past, this has been achieved by drying in a grain bin with a false perforated floor; such systems are very unusual today, although are often seen at large grain processors or mills.

The most commonly found technology for storage drying in the UK is utilising a shed with a ‘drying floor’, sometimes referred to as ‘on floor’ drying. Grain is heaped to a level depth up to 2.4m over a system of air distribution ducts built on top of or into the shed floor. Using a suitably sized fan large volumes of ambient or slightly heated air are blown through the crop; it may take a couple of weeks to achieve the correct moisture content. There is very little scope for automated management of this technology and this can be problematic. Whilst installing a drying floor in an existing shed may be the cheapest route to having a grain drying capability, it is also perhaps the hardest technology to operate well.

If heat is used when the entire mass of grain is still wet, the low RH hot air can take moisture out of the grain at the bottom but then deposit it in the still wet and cold top layers as condensation. Even when this is avoided, by using ambient air until the mass of grain achieves some level of moisture reduction, the grain will still dry in layers with very dry grain at the bottom of the heap and layers of gradually increasing moisture towards the surface.

Drying floors come into their own due their versatility and can be found operating year-round, drying materials from grass and forage crops, to woodchip for biomass fuel, to wastepaper pulp. The slow rate of drying means that this technology is much less energy intense than other faster systems; it is also possible to supply the heat from most forms of generation, biomass hot water fed drying floor systems have become commonplace across the UK in the last 10 years.

Figure 4: An on floor drying grain store.

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Figure 5: A grain store with floor drying. Note grain is not being dried in the photograph but just stored. See also stirrers to move grain and improve drying efficiency and preserve quality in storage.

Review outcome and recommendation

There is little information available concerning how best to operate drying equipment and very little knowledge on the basic principles drying crops. What information is available is often provided by a party with a vested interest in selling equipment. A one stop shop grain drying guide would offer a huge amount of benefit to the industry, information should be accessible and form an impartial guide to the benefits of different technology and the process one is trying to achieve when drying grain.

The work proposed regarding quantifying energy use in theoretical sense and in practice would inform the recommendation above.

Information available to the operator

A large part of this review was to review the available information regarding theory and techniques in regards grain drying equipment and its use. The following table details the findings so far:

Title	Literature type	Source	Subject Matter	Publication Date	Comments
How to dry grain more efficiently in a wet harvest	Magazine article	Farmers Weekly	Practical advice on grain drying aimed at the farmer.	22/10/2020	Includes comment from several drying equipment installers and manufacturers but is well balanced. The focus of the article is how drying efficiency can be improved by installation of new equipment or modernisation of existing equipment, this is insightful, but the article contains only a brief mention of better management. The best of multiple grain drying articles available from the farmers weekly archives, most are disguised marketing for an equipment manufacturer or installer.
Grain storage – It's the system not the size that matters	Magazine article	CPM Magazine	Case study of an on farm dryer improvement project.	22/07/2016	As with most press case studies this publication focuses heavily on one technology and manufacturer and is not entirely impartial. The article does discuss drying theory and makes the rarely discussed point about using cool air to avoid a humidity spike when drying warm grain. Only grain drying material available from CPM Magazine
Grain drying with a renewable difference	Magazine article	Farmers Guardian	Case study of an on farm dryer improvement project.	19/06/2020	Anecdotal, not particularly informative and includes some technical inaccuracy, however, gives a detailed description of a new on farm drying system utilising renewable energy in the form of solid biomass to improve drying

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					efficiency. One article from a limited drying output by Farmer's Guardian.
HGCA Grain storage guide for cereals and oilseeds	Handbook/Guide	AHDB	Informative guide regarding the storage of cereal crops	First published in 1999. 2nd Edition 2003. 3rd edition published Autumn 2011	Although the bulk of this publication does not directly concern grain drying there is a short section including basic drying theory although only with a strong focus on conserving grain quality for food safety. Only grain drying material available from AHDB. Freely available online.
Grain drying and storage – A Farm Electric Handbook	Handbook/Guide	The Electricity Council/ NFU Energy	Handbook	Circa 1980	Very detailed with good high-level explanation of the scientific processes which need to be achieved in order to dry effectively. Very out of date in terms of equipment, sizing, some farm practices and crops. Not always accessibly written but still the best resource available in the authors opinion. Only available for sale second hand when a copy comes up.
Optimising the use of grain stirrers to enhance on-floor drying	Research report	HGCA/AHDB	Findings of a research project	2013	The results of an in-depth modelling of the use of grain stirrers under two different sets of circumstances. Interesting and very useful results but although freely available online written in such a way as to be inaccessible to the public. Needs to be interpreted and presented.
Optimising the use of grain stirrers to enhance on-floor drying	Research report	American Grain Elevator and Processing Society	Findings of a research project	July 2002	Very detailed high level dissection of grain drying in the US, includes detailed descriptions of theory and analysis methods. Large amounts of this report are applicable to the UK although extra interpretation required to decipher exactly what. Although freely

					available online written in such a way as to be inaccessible to the public.
Energy efficiency in grain preservation	Doctoral thesis	University of Helsinki Department of Agricultural Sciences	Findings of a research project	October 2016	Detailed dissection of grain drying from an energy efficiency point of view. Has a Finnish perspective but largely applicable to all of Europe. Very good resource but needs interpreting to be used practically.
Overview of new techniques rod drying biological materials with emphasis on energy aspects	Scientific Journal	Brazilian Journal of Chemical Engineering	Findings of a research project	June 2005	Interesting dissection of technologies which are not commonly found in the UK or anywhere else but could be utilised to dry grain. Could be interpreted to help formulate ideas for the replacement of fossil fuels used for drying.

Review outcome and recommendation

It's unfortunate that much of the information available is either many years old or proprietary information made available by manufacturers and suppliers of equipment. Whilst much of the underlying theory has not changed, the technologies and equipment described in historic literature needs updating for a modern farming audience. Similarly, the impartiality of manufacturers and suppliers' information cannot be relied upon, where sale of equipment is the ultimate end game, and therefore the benefits and pitfalls of any particular technology may not be fairly represented.

A steering group of cereals farmers would be invaluable in ascertaining which literature would be the most important to bring up to date for the modern audience and to critique the work such that it retains relevance and impartiality.

Approaches to energy use for grain drying

Energy efficiency

Through discussion with consultants, farmers and installers, a table of energy efficiency recommendations has been compiled below. During consultation, it became apparent that there is a range of approaches to energy efficiency; one installer confirmed that they annually check systems for their clients prior to the drying season but several farmers confirmed they do very little to maintain their system beyond the absolutely necessary for continued operation.

Area	Problem	Action
Fans	The fan is the most important part of a drying system and often the greatest consumer of energy.	Check for corrosion and damage, clean the blades thoroughly and have the fan performance tested to check that it reaches the correct speed and output.
Motors	Wherever an electric motor is deployed, whether in the form of a fan or a drive, energy is usually being wasted, as motors are rarely sized to match the mechanical load they serve. Furthermore, motors may not operate at the ideal speed for the service they provide – any excess speed representing a waste.	It is sometimes viable to replace a motor purely for energy efficiency gains however when a motor needs to be repaired or replaced the best economic case can be made and installing the most efficient motor should be considered. Synchronous AC motor efficiency has improved since a lot of older equipment was installed and exhibit an efficiency perhaps 8-10% better than older designs. All motor driven fans and machinery should be checked for condition and properly lubricated and serviced to eliminate friction losses. Motor speed is now readily controllable through use of an inverter or Variable Speed Drive. These electronic devices regulate speed by supplying the motor with variable frequency power, from full speed 50Hz down to 20Hz. Motors obey a law of physics known as the Cube Law, which states that power consumed is proportional to the cube of speed – which means that at 90% of full speed, only $(90\%)^3$ = 73% of full power is drawn; and at half speed this falls to just 13%. Finally, the latest motor technology combines all these advantages into the Electronically Commuted (EC) motor. It is inherently efficient and speed-controllable through integrated electronics with no need for a separate inverter.

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Inlet and exhaust vents Air ducts Drying floors	Air is the working fluid of a drying systema and must be allowed to reach the grain in the most efficient way possible and discharge wet air as easily as possible Inadequate or badly designed inlets and outlets can restrict airflow in and out of the dryer. Air leakage from ducting leads to less effective drying. Drying floors are regularly damaged by machinery during emptying, perforations can also be blocked by broken grain or admixture, underfloor ducts may also be filled with grain from a leaking floor.	Check that the inlet and exhaust are of a suitable size and clear of any obstructions. Inspect ducting and repair leaks. Thoroughly clean floors and ducts between crops, inspect for damage and repair as necessary.
Store loading/capacity creep	Drying floors need to be loaded evenly and at the correct depth to ensure even drying.	Ensure floor is loaded level and to the correct depth. Do not be tempted to load a floor too deep.
Heaters and coolers	Inoperable, inadequate or inefficient heaters and de-humidifiers can prolong drying times and increase energy consumption.	Ensure heaters, de-humidifiers, and coolers are serviced and maintained regularly.
Controls and sensors	Both automated and manual drying systems base the management of the dryer on sensors and moisture meters. The accurate and appropriately located recording of grain conditions and air parameters is therefore paramount to making the right control decisions and not wasting energy.	Ensure automated systems are fully operational and calibrate sensors and meters at least annually.
Lighting	Drying systems are often operated for long hours	Check lighting is clean and in good order, replace lighting where possible with LEDs.

	and during the night and need large lighting installations for safety and ease of operation.	

Improper operation

One significant factor that has become apparent during the research process for this review is the misunderstanding or lack of understanding of how the drying process really works. This problem manifests itself in poor, inefficient or even incorrect operation of grain drying facilities. A real opportunity for making serious improvements to grain drying energy efficiency would be to improve the standard of operation.

Issue	Explanation
Over drying	One of the most common instances of a lack of efficiency is the over drying of grain; this is particularly common with storage dryers but does happen with all technologies. The problem stems from a lack of fine control and a 'too dry is better than too wet' approach; it is estimated that significant energy is expended drying grain past the point where it becomes safe to store.
Inappropriate use of heat	The proliferation of biomass heat has led to many drying floor systems being retrofitted with water to air heat exchangers. On floor drying, systems can be considerably harder to control when the air is heated. Hot air can cool on contact with relatively cool grain and deposit moisture into the heap; time drying will heat the grain and overcome this effect, however, the air is then prone to dry the lower layers very effectively and saturate before being exhausted repeating the problem by depositing moisture in the upper layers. The grain in the lower layers is over dry by the time the upper layers reach the desired moisture content. Whilst using heat in a storage dryer may speed up the drying process, it is often the case that far more energy has been expended than necessary and a proportion of the heap is too dry. Grain stirrers can make the use of a drying floor with heat more controllable, however, the user must understand what they are trying to achieve before adding another energy consuming process into the mix. It should be acknowledged that many of the systems dealt with here will have heat consumption incentivised by the RHI.
Drying at the wrong time	The operator of a drying system must appreciate how ambient humidity and air temperature will affect the process. As mentioned, when discussing the inappropriate use of heat, hot air hitting cold grain may have not achieve the desired affect and the opposite is also true. A drying floor or bin loaded with hot grain can be dried using ambient warm

	air, however it could be dried more efficiently if the air was cold. Cold night air on contact with warm grain would immediately rise in temperature, this would have the effect of reducing the RH of the air and giving an increased capacity to absorb moisture as it travels through the heap.
Overloading	Harvest time is often high pressure and never more so than in a particularly wet year. The danger for a dryer operator in a wet year is the temptation to overload their equipment in the hope of increasing throughput and keeping the combine going in the windows between rain. Not only will the grain take longer to dry, but the relationship between load and energy consumption is not linear; the operation will therefore be considerably more energy intense than it would have been had the equipment been loaded as per its design.
Control and data	Management systems vary from basic humidity/temperature sensors or nothing at all to much more complex management systems. This comes down to the low return on investment when upgrading an existing grain drying system. Control systems have been revolutionised by the availability of cheap electronics and sensors. The application of good control requires good data acquisition and the intelligent analysis and application of that data. Time spent altering control settings and tailoring them to get the best outcome is rarely wasted and the availability of cheap wireless sensors, powerful computers and widely available tools and manipulation lends itself well to providing great opportunities for energy efficiency from control in the future. The acquisition and use of data has the potential to be truly revolutionary for smart farming of the future. Relevant data, intelligently interrogated, allows efficiencies in energy, labour, processing times etc. to be identified and production to be boosted by concentrating on the detail and making the small incremental changes that add up to large benefit. However, data for data's sake and misinterpretation can be just as harmful so clear understanding and explanation of the benefits and changes are necessary.

Review outcome and recommendation

We would recommend regular description and reinforcement of the principles of good energy efficiency in drying; especially pre-season when changes can be made easily and with good effect. Articles in farming journals and posters of top tips or similar can be very effective.

Control systems, which allow more precise control and the ability to set and monitor parameters via a user friendly interface or remotely via a tablet or smart phone, are *becoming available. A review of such systems should be conducted to understand what they offer and benchmark the savings*.

The work proposed regarding quantifying energy use in theoretical sense and in practice would inform the recommendation above.

Other energy uses

Grain Cooling

Some grain drying systems cool the grain before it exits, so that it is as an appropriate temperature to store. Poor design or heat utilisation can lead to grain that is too hot and requires significant cooling after being dried. This is typically done by moving ambient or cooled air through the grain using fans, the resulting dry warm air is then vented. In systems where grain cooling is implemented, there is potential for heat recovery via either heat exchangers and a heat upgrade tank; or when multiple batches of grain are being dried, direct recirculation through damp grain.

Grain cooling is however not limited to being a component of a drying system but should also be viewed as a process by itself; large refrigeration units are sometimes employed to cool grain in store, this is particularly used in bins where a lack of insulation leads to a considerable heating effect from the sun. Discussion with industry representatives in the preparation of this report highlighted a significant lack of understanding regarding how to utilise grain cooling for best effect or indeed whether it should be utilised at all.

Grain Stirring

Grain stirrers are usually found installed in bulk drying stores or silos, their purpose is to mix the grain continuously to avoid the development of layers of different moisture contents, which are a pitfall of storage or bulk drying.

An AHDB/HGCA project titled ‘Optimising the use of grain stirrers to enhance on-floor drying’ was published in September 2013 and modelled the effect of using grain stirrers. The project found that, in ambient conditions, stirring reduced over drying and certain toxins but did not improve the drying efficiency; this was because stirring improved drying on the surface of the heap, the dry surface was then wetted by the air being exhausted from the heap. The project also concluded that when drying with heated air of low RH, stirring the grain sped up the drying process and lead to efficiency improvements both in reduced heat and electricity consumption.

Lighting

Grain drying, as with many harvest operations, will often be operated into the night; grain storage and drying are also activities which often take place within buildings. These factors mean that there will often be a large lighting load during the grain drying season.

Improvements in LED lighting technology have brought well-understood energy savings to agriculture, but also new benefits through aspects such as lowered fire risk.

LED lighting operates at lower temperatures. This eliminates the fire risk posed by the control gear of older lighting, which could literally burn out at end of life, posing a hazard in a dusty environment. LED lighting may also be dimmed and switched off for brief periods without a prolonged restrike delay.

Review outcome and recommendations

Work has been carried out in these areas, but the main messages require reinforcement as they seem to have been lost over time.

Some update work will be required to ensure the messages are appropriate and the current prices and costs for technology are refreshed.

Alternative and future technology

Although energy consumption and capital cost are thought to be high, there is potential for electromagnetic drying plants to become a more mainstream technology. There is little information available outside of various pieces of academic research, however there is at least one manufacturer offering plant for install on farms in the UK. The principle is to use electromagnetic waves in the form of infra-red, or micro-wave, waves to heat the water molecules within the grain and force them to the surface. Airflow can then be used to carry away the liberated moisture in the manner of other grain drying technologies. The air would still need to have the humidity deficit required to achieve this, but research suggests drying times could be reduced.

Review outcome and recommendations

The identification of this technology demonstrates that there is new equipment and thinking about improving grain drying. The appraisal of systems such as the one described is important to provide quality factual and impartial data to farmers so they can make the right business decisions in terms of investing.

Energy provision

Grid electricity, capacity and sizing effects

Whilst not all drying systems employ heat, nearly every modern system employs electricity - excepting those driven directly by a tractor PTO. In considering drying technology, electricity consumption and issues surrounding it is important; an understanding of these issues can explain some of the costs and how to perhaps avoid them.

Many efficiency improvements rely on the availability of accurate data against which to establish a baseline. The savings potential of a proposed investment can then be established, and the returns evaluated against the cost. Energy consumption may be known as monthly totals through a billing meter or heating oil invoices, but the addition of submeters will allow main systems to be considered in isolation. Metering that produces half hourly consumption data allows a profile to be observed and this assists with detecting events associated with waste.

Energy costs

Electricity (and gas) prices have been in almost relentless increase since late 2020; in addition, energy costs have had considerable additions of non-commodity cost to cover the investment into renewables production and to tax for its carbon emissions. There are techniques to reduce cost, such as flexible purchasing or avoiding high cost periods within a day that may provide benefit to those drying grain. The potential for this needs to be established and costs/benefits and risks explained.

ASC Spiking

The DNO will apply a charge to a site with half-hourly metered electricity supply called the Agreed Supply Capacity (ASC). This is essentially a reserved electrical capacity to that supply, so that it can be called at any time. These are common at sites with grain dryers, because there is often a large electricity import spike when they are in operation. Although this spike in import will only occur for around 2 months of the year, ASC charges are paid all year round. This means that peak reduction through energy efficiency, electrical control, on-site generation and energy storage can lead to reasonable cost decreases.

Soft start

When a motor is turned on, it must accelerate up to its operating speed from zero rpm, this requires a large amount of torque and causes a big spike in power demand. This is problematic for various reasons, it is inefficient and consumes large amount of power, it can overload the electrical system on site, it will cause spikes in demand which can cause problems with grid supply capacity and ASC spiking, it is also bad for the motor and any drive train components. The solution to this problem is to fit the motor with a 'soft start device'. When a motor fitted with soft start is turned on, the voltage to the motor is limited and gradually increases; this gradual controlled acceleration to operating speed causes a significantly smaller spike, mitigating the issues highlighted above.

Appropriately sized transformers

Linked to soft start, if a transformer is owned by the farm and was sized for older motors it may be larger than currently required. Smaller transformers will consume less energy and be easier to manage.

Three phase v's single phase

Single phase alternating current forms a sinusoidal wave; the frequency of the wave is 50Hz in the UK, meaning that the cycle is repeated 50 times each second. Whilst this is fine for most low load applications, the fact that between the two peaks the power drops to zero is problematic when running equipment such as large motors under high loads. The solution is three-phase power. In a three-phase power supply, two additional supplies are added; the two additional supplies are each out of sync with the first and each other, which means that power on or near a peak of the wave is always available. Three phase power is an important factor when installing drying equipment, as the availability of three-phase on the site dictates the size of equipment which can be installed.

Whilst three-phase will be slightly more efficient than large single phase motors, the biggest benefit is the physical size reductions in equipment, alongside allowing more powerful equipment and the improved reliability in operation.

Tractors v's electric on grid

Sometimes, running a generator set or a tractor mounted PTO generator is cheaper than electricity imported from the grid; if factors such as reducing the ASC spike and mitigating grid connection constraints are factored in, it may look attractive. It is worth considering however that in the coming few years, agriculture will have to reduce reliance on fossil fuels because they are less sustainable.

Renewable electricity

Solar PV

Probably the best recognised and most established of technologies, Solar PV, is undergoing a quiet revolution where installing panels with improving efficiency and reducing cost is becoming a de-facto part of many buildings and projects. The best economic return for solar PV is made where the generated power can be used onsite when it would otherwise be imported from the grid. This will only happen when loads are of a similar scale and occur during the daytime. Especially where there is a heavier reliance in summer, such as with grain drying. The downside to solar PV for grain drying applications is the almost total lack of load out of the grain drying season; this may extend the payback period for solar PV in a purely grain drying orientated system. This problem can be addressed by shifting more consistent loads throughout the rest of the year to match the profile of solar generation and minimise import further. Where a mismatch cannot be avoided, such as a large lighting load during the rest of the year, battery storage could provide a useful solution.

Onshore wind

Set for a resurgence in the coming years (because of the need to balance seasonal PV generation and provide support to remaining power stations), wind power is closer matched to consumption profile than PV. Sites with large grid capacity (for fan load) would have electrical suitability for a turbine, although wind speeds may need to be ascertained, as would considerations on locality and possible opposition.

Battery storage

The drawback with renewables, such as solar PV and wind, is the fact that their power may be generated at a time when it is not required, resulting in export to the grid with far lower resulting income (or cost avoidance). Charging electrical storage batteries as a short-term measure, to soak up additional generation for consumption later or to export when the price is better, is a utopian solution. Similarly, where producers employ an energy purchasing strategy, attempting to avoid expensive periods or to benefit from cheap or negative energy prices, batteries could provide a short-term load or supply.

Although electrical storage batteries are often discussed as being the solution to the variability of renewable generation, the cost of them is still too high of themselves to warrant the investment. Most batteries and large battery installations have been deployed in ‘in front of the meter’ grid support services, where they are available to the grid to react very speedily to out of specification power provision, such as over or under voltage and frequency response. There are limited ‘behind the meter’ installations, which are the preserve of domestic users and enthusiasts. Having said this, the cost of batteries is reducing, and the market dynamics are changing quickly. Therefore, battery storage may soon become viable for price arbitrage (when the mismatch between supply and demand is clear, repeatable, and reliable), or where consumption cannot be avoided at peak tariff periods.

CHP

Combined heat and power generation could be used to provide electricity for drying installations and is discussed in detail in the Heat section. However, because of its reliance on fossil fuel and the seasonality of use, the capital costs are unlikely to prove beneficial.

Renewable heat

A farm drying system is most likely to use heat provided by either oil or gas; within the last 10 years there has been a proliferation of renewable heat thanks to the Renewable Heat Incentive, however the cheapest and most reliable option for high temperature heating has remained oil or gas. Cheap fossil fuel is unlikely to be a long term option and the industry should therefore not only look at reducing use through improved efficiency, but also by de-carbonising heat sources.

Biomass boilers

One of the most common methods of renewable heat generation, biomass combustion, has seen a steady increase in uptake since it was eligible for payment on the non-domestic Renewable Heat Incentive (RHI) scheme. This scheme started in November 2011 and closed to new applicants in March 2021.

A result of the popularity of the RHI scheme, the price for biomass, particularly woody biomass, has increased greatly. This means that for a system which is not incentivised by the RHI, it would be much more difficult to have biomass combustion make financial sense compared to traditional fossil fuel combustion. However, non-woody biomass such as agricultural residue is less expensive. Thanks to the RHI scheme, there is now an extensive industry serving biomass boiler operators and there is also precedent for significant purchase price reduction following the withdrawal of incentives. These factors may help to keep biomass heat relevant.

This makes it difficult for grain drying as a sole heat use, because of the variability in heating demand each year. However, if there is a biomass boiler currently supplying to other nearby heat uses, connecting a grain dryer can provide a late summer heating load that may not otherwise be present.

Heat pumps

Dry air is more effective at drying than hotter air with the same RH, it does not need the high temp (circa 100°C) to dry quickly. The most practical way to benefit from principle would be to de-humidify air before heating it. De-humidified air could make lower temperature heat generation, such as that supplied by various renewable heat generators, more useful to a high output drying system.

We have seen several recently installed ground source heat pump (GSHP) systems in the UK, which utilise a heat exchanger in the refrigerant circuit as a de-humidifier drying the air pre the hot water heat exchanger in the hot water heating circuit.

Figure 6: Heat exchangers in front of floor dryer intake fans. In this ground source heat pump system has a ground loop heat exchanger directly in front of the hot water heat exchanger. This condenses water vapour drying the air before heating. De humidifying in this manor leads to a greater humidity deficit than is achieved by heat alone. Note the drain on the heat exchanger unit for condensed water.

CHP

CHP stands for combined heat and power and usually refers to plant such as an engine and generator set, which generates power and provides useful heat harvested from the engine cooling and exhaust gases. CHP plants are not usually viable on a small scale and perform best when operated on an almost permanent basis; these characteristics mean that for a seasonal demand, such as grain drying, CHP is not immediately applicable, however, for a site with other large heat and power demands or with an existing CHP plant providing energy to a grain drying system can benefit in reduced energy costs. This is particularly interesting when there is potential to site a grain drying facility next to an existing CHP operator who could provide both heat and power by agreement.

Renewable CHP

Biomass CHP refers to plant usually consisting of a biomass boiler producing either hot water or steam and an Organic Rankine Cycle (ORC) turbine or steam turbine respectively. Plants are not that common due to the high installation cost and often quite poor electrical efficiency, however incentive schemes in the past have made the technology more viable.

Biogas CHP generally refers to engine and generator sets running on biogas often produced by anaerobic digestion, although the gas may have been produced from the gasification of biomass; this is rare however as gasification plants are prone to reliability problems usually caused by ‘dirty’ gas produced when running on anything but the cleanest, driest and most uniform biomass. Anaerobic digestion is an established technology that is familiar to many farmers and producers. The process digests crops, agricultural and other biological wastes, to produce biogas which may be burned in an engine to produce electricity, heat or refined for injection into the national gas network. The digestate may still be nitrogen-enriched for use as fertiliser. The process is incredibly intense, and most operators will re-divert a significant proportion of their farming operation to feeding and emptying the digester; for a seasonal load such as grain drying, it is entirely unsuitable unless there are other significant demands on site. The processing of grain is an eligible heat use under the RHI regulations so there is significant opportunity for existing plants to add provision for supplying heat to a grain dryer to their existing system.

Review outcome

The section above describes in broad terms the issues and technologies that cereal farmers will need to understand and manage as we transition to a lower carbon future, benefit from incentives or simply to protect from energy price rises. Existing operators of renewable and non-renewable plant may not be fully aware of the opportunities to utilise their generation for drying.

For example, there are big opportunities for alternative energy sources, especially heat sources such as heat pumps, which can also be utilised to de-humidify air.

We would recommend a programme of work to identify the seasonality in requirements and the intra day requirements for energy, such that clear messages about the benefits and risks of the approaches discussed above can be provided to farmers. Publications in Horticulture such as GrowSave Tech updates and GrowSave Energy News would be ideally suited to this messaging, distributed via inserts in existing publications or email newsletter.

Summary & recommendations

The table below brings together all the recommendations made in this review, to consolidate this further still the work can be described in the following three areas:

Technologies

Large amount of old equipment still in use, there is potential for electrification, automation and greater utilisation of renewable heat and power generation.

Practice

A significant proportion of operators do not understand the technical details of what they are trying to achieve when drying grain. Education is needed about how to operate drying facilities to optimise their performance and to operate existing equipment more efficiently.

Resources

Readily available resources are out of date or produced with the purpose of selling a product. Some old resource could be updated and re-published to benefit a fresh audience. New impartial resources would also be useful. There is up to date academic work available, but it needs to be interpreted to provide useful practical information.

Research area	Review	Potential Growsave work
Principles of grain drying	In preparing this report, many discussions were had with drying system operators and farmers. The level of knowledge on the principles of drying and how air contains moisture, the consequent effect of temperature and potential for dehumidification seems to require improvement.	We recommend a series of training courses/materials on the principles for relevant staff that will enable the right decisions to be made under differing drying conditions. The energy requirement for grain drying is not well publicised; much of the literature references theory (which will be largely unchanged) but agricultural practice and technology efficiencies have moved on. Further work would benchmark the different drying approaches and carry out monitoring of several different grain drying systems to ascertain current practice and thus potential for efficiencies. This is a theme that covers the sections on technologies and energy efficiencies that follow.
Grain drying technologies	There is little information available concerning how best to operate drying equipment and very little knowledge on the basic principles drying crops. What information is available is often provided by a party with a vested interest in selling equipment.	A one stop shop grain drying guide would offer a huge amount of benefit to the industry, information should be accessible and form an impartial guide to the benefits of different technology and the process one is trying to achieve when drying grain. The work proposed regarding quantifying energy use in theoretical sense and in practice would inform the recommendation above.
Information available to the operator	It's unfortunate that much of the information available is either many years old or proprietary information made available by manufacturers and suppliers of equipment. Whilst much of the underlying theory has not changed, the technologies and equipment described in historic literature needs updating for a modern farming audience. Similarly, the impartiality of manufacturers and suppliers' information cannot be	A steering group of cereals farmers would be invaluable in ascertaining which literature would be the most important to bring up to date for the modern audience and to critique the work such that it retains relevance and impartiality.

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	relied upon, where sale of equipment is the ultimate end game, and therefore the benefits and pitfalls of any particular technology may not be fairly represented.	
Approaches to energy use for grain drying		We would recommend regular description and reinforcement of the principles of good energy efficiency in drying; especially pre-season when changes can be made easily and with good effect. Articles in farming journals and posters of top tips or similar can be very effective. Control systems, which allow more precise control and the ability to set and monitor parameters via a user-friendly interface or remotely via a tablet or smart phone, are becoming available. A review of such systems should be conducted to understand what they offer and benchmark the savings. The work proposed regarding quantifying energy use in theoretical sense and in practice would inform the recommendation above.
Other energy uses	Work has been carried out in these areas, but the main messages require reinforcement as they seem to have been lost over time.	Some update work will be required to ensure the messages are appropriate and the current prices and costs for technology are refreshed.
Alternative and future technology	The identification of this technology demonstrates that there is new equipment and thinking about improving grain drying.	The appraisal of systems such as the one described is important to provide quality factual and impartial data to farmers so they can make the right business decisions in terms of investing.

Energy provision	The section above describes in broad terms the issues and technologies that cereal farmers will need to understand and manage as we transition to a lower carbon future, benefit from incentives or simply to protect from energy price rises. Existing operators of renewable and non-renewable plant may not be fully aware of the opportunities to utilise their generation for drying. For example, there are big opportunities for alternative energy sources, especially heat sources such as heat pumps, which can also be utilised to de-humidify air.	We would recommend a programme of work to identify the seasonality in requirements and the intra day requirements for energy, such that clear messages about the benefits and risks of the approaches discussed above can be provided to farmers. Publications in Horticulture such as GrowSave Tech updates and GrowSave Energy News would be ideally suited to this messaging, distributed via inserts in existing publications or email newsletter.