Recommendations on FEFTS future research

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Abstract

This document provides research recommendations on how Fossil-Energy-Free Technologies and Strategies (FEFTS) can be adopted within European farming to defossilised agricultural activities and the respective products.

After introducing the project objective, the description of the methodology to extract the information from all project's activities was provided. The combination of the literature review of current energy status in EU agriculture, a survey with farmers and experts about FEFTS adoption, the online AgEnergy Platform content, and the interactive innovation processes through workshops in national and transnational level provided the research recommendations on how agricultural defossilisation could be achieved faster and more effectively.

A list of research recommendations is provided, per theme of agricultural production (open-field, greenhouses, livestock).

The proposed research topics could be used by research officers in national and EU level to develop new research calls in Horizon Europe, Structural Funds for R&D activities, Sectoral R&D programmes, Erasmus+, The Life programme and national initiatives in member states to assist in the faster establishment of a Green Europe.

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1. INTRODUCTION

AgroFossilFree is a Horizon 2020 CSA project whose main objective is to create a framework under which all core stakeholders cooperate to evaluate and promote the currently available fossil-energy-free technologies and strategies (FEFTS) in EU agriculture to decrease in the short term and eliminate in the long run the use of fossil energy in open-field crop production and controlled environment agricultural constructions from cradle to farm gate, while maintaining yield and quality of the end product offered to consumers in a cost efficient manner. Such a framework will contribute to bridging the gap between the available novel high-end clean energy solutions and the everyday European agricultural practices by capturing grassroots-level needs and ideas, promoting effective exchange of information, and investigating the possible financing opportunities for any de-fossilizing activity between the farming and related industry community. Ultimately, it will facilitate farmers to find solutions for their specific needs contributing towards fossil-free farming.

AgroFossilFree activated and ran for 36 months an effective exchange between research, industry, extension services and the farming community so that direct applicable research and commercial solutions on FEFTS are widely disseminated and grassroots level needs and innovative ideas thoroughly captured.

Using the EIP-AGRI "multi-actor approach", AgroFossilFree has gathered insights on the barriers and incentives for the adoption and better uptake of novel FEFTS as well as on the needs from end-users and other stakeholders in the value chain, such as researchers, industry, and advisors. These findings were used to produce a set of research recommendations to assist the fast adoption of FEFTS in European agriculture, which are presented in this Deliverable.

The Deliverable is divided into six Chapters:

Chapter 1 – Introduction: Short overview of the project objective, the approach selected, and the results obtained.

Chapter 2 – Methodology: Description of all steps to extract the information from the respective project's activities (literature review of current energy status in EU agriculture and interactive innovation processes through workshops in national and transnational level) and provide the research recommendations on how agricultural defossilisation could be achieved faster and more effectively.

Chapter 3 – Main Research Recommendations: Main results that contributed to identify policy gaps and respective solutions on regional and EU level, which should be addressed by Horizon Europe, Structural Funds for R&D activities, Sectoral R&D programmes, Erasmus+, The Life programme and national research initiatives in member states.

Chapter 4 – Conclusions

2. METHODOLOGY

AgroFossilFree applies an interactive innovation model, based on a bottom-up approach, to extract research propositions from all types of stakeholders (farmers, advisors, innovation brokers, FEFTS providers, researchers, and policy makers). The project activities and respective results that were summed to produce the research recommendations of AgroFossilFree project are shown in Figure 2.1.

The first step of this process is the identification of research gaps that were found from the extensive literature review of metadata about energy status in EU agriculture. After consulting a series of scientific publications, EU statistics and grey literature (in some cases), the AgroFossilFree consortium managed to recognize some research roots that would assist and facilitate the analysis of agricultural energy profiles along the production categories in EU farming. The full analysis of the literature review can be found in Deliverable 1.1.

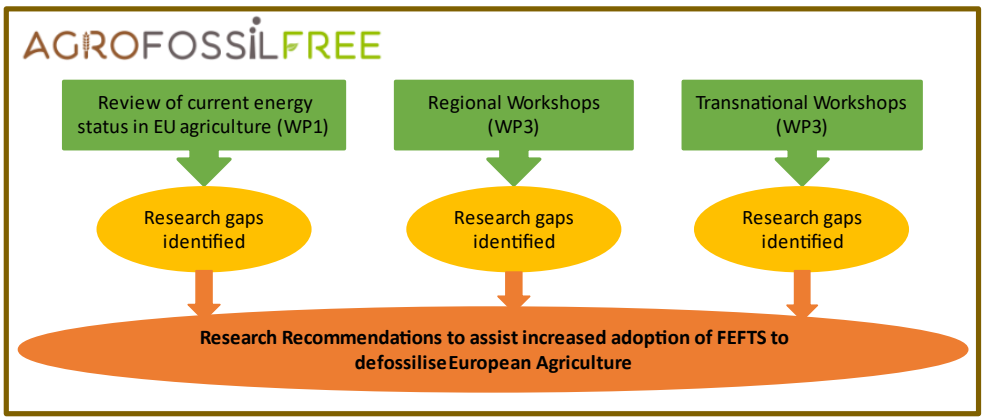

Figure 2.1. Project results that have been considered to produce research recommendations. (Green boxes represent activities and orange bubbles represent results).

The second step towards the full list of research recommendations was to use the open discussion with all types of stakeholders in the 24 regional workshops on a national level, where ideas that are more directed to local needs were obtained. The full analysis of the research ideas and how they were extracted is given in Deliverable 3.3.

Finally, the third step was to validate the research ideas obtained in the regional level and produce further insights on research from combined ideas between stakeholders of different countries in the thematic transnational workshops. The process and the detailed results of research propositions in these workshops can be found in Deliverable 3.4.

Therefore, the combination of the research ideas given in each of these 3 steps has assembled the main research recommendations to solve problems of existing FEFTS and open the route to new FEFTS that will be efficient, reliable and compatible to existing technology in order to be easily adopted by farmers and assist the rapid defossilisation of agriculture.

The following sections present in brief the project's outcomes that have been considered to produce the research recommendations. For details on the methodology used to produce the individual outcomes and results, the reader is referred to the individual Deliverables.

3. MAIN RESEARCH RECOMMENDATIONS

3.1. Current energy status in EU agriculture

AgroFossilFree has applied an operational definition of energy use in agriculture and attempted to include all operational energy use that is covered by agricultural activities and uses, both directly and indirectly. The system boundary was cradle to farm-gate and included all energy consumption up until the farm gate. Direct energy use refers to all energy inputs consumed for: on farm operations, transportation, heating and cooling, lighting, electrical equipment, machinery, automation processes, farm management and irrigation. While the main direct energy uses vary depending on the production system, in our study it was allocated according to three sectors: open-field agriculture, livestock and greenhouses. The main energy uses that the study focused on for each category were:

- Open-field agriculture (sowing, planting, tillage, application of inputs, harvesting, machinery use, irrigation and threshing, storage, grain drying).
- Livestock (crop processing and feeding, milking processes, manure handling, heating, cooling, dehumidifying and ventilation, machinery use, water heating and pumping and lighting).
- Greenhouses (on farm operations, heating and cooling, lighting, and irrigation).

Indirect energy use refers to all the energy used to produce agricultural inputs. These inputs account for energy use that can be assigned to the agricultural sector but is used prior to reaching farms, including energy used in the:

- production of fertilizers (raw materials, manufacturing, transport)
- production of pesticides (raw materials, manufacturing, transport)
- production of animal feed (includes all the energy use to produce animal feed, including its raw materials)
- pumping of water to the agricultural holding
- production, storage and transportation of seeding materials

The results of this extended metanalysis of information coming from different sources of scientific literature and statistics (see Deliverable 1.1.) showed the following:

Energy use in EU agriculture is **significant and fossil fuel dependent**. According to Eurostat, agriculture accounts for 3.2% of total energy consumption, 56% of which is derived directly from crude oil and petroleum products, 17% from electricity, 14% from gas and 9% from renewables and biofuels. However, our results suggest that if indirect energy use associated with the production and transport of fertilizers and pesticides is included the proportion of energy use in the EU-27 would be **62% higher overall**.

Our results also show that energy use, its concentrations and breakdown, **vary significantly per production system** (open-field, livestock, greenhouses). According to our estimates, of the crops and production systems included in our study, the annual energy inputs for arable agriculture are 1227 PJ, for orchards and vineyards are 208 PJ, for meat production systems are 501 PJ, for dairy production systems are 543 PJ.

For open-field agriculture, our study finds that the **production and use of fertilizer is the largest energy consuming activity in EU agriculture, accounting for around 50% of all energy inputs**. On farm diesel use accounts for 30%, while electricity (for irrigation, storage and drying) accounts for 8%. Pesticides and seeds each account for 5% of total energy inputs. In all livestock systems, except for beef production systems, **animal feed is the main energy input accounting for around three quarters of all energy**

requirements. The production of animal feed consumes around 60% of the cereal production in the EU and requires significant high-protein imports. On farm electricity use, which currently mainly comes from fossil sources, is also significant but varies considerably depending on the production system. In high yielding and high-energy intensive greenhouses energy use is dominated by **heating and cooling**. By contrast, lower yielding and less energy-intensive systems use little to no heating/cooling and instead energy use is mainly associated with **fertilizers, diesel use for machinery, irrigation** and other activities.

The above illustrate that for the EU to achieve the goals outlined in the Green Deal and Farm to Fork strategy, it is likely that the **adoption of non-fossil energy sources, and improvements in energy efficiency** and the further development and adoption of related technologies for agriculture is required. In addition to this, a **transition to more sustainable agricultural practices and farming systems is required**. For instance, our chapter on conservation agriculture, as an indicative example of a FEFTS, highlights that scaling of conservation agriculture can significantly reduce on farm energy use and carbon emissions as well as sequester considerable amounts of carbon (**up to 190M tonnes per year**) and improve the overall climate resilience of the agricultural sector.

3.1.1. General Research Ideas

Providing an overview of energy use in EU agriculture is a challenging topic due to the plethora of the **available, and in most cases inconsistent, data**. However, there are multiple areas that would benefit from further research.

- Our understanding and estimates of energy use in EU agriculture would benefit from **additional studies on energy use in all three main production systems, especially for greenhouse agriculture**.
- Research on the **impact of farm size on energy use** and **how unification of small holdings** either by acquisition from larger farms or by applying modern cooperative systems between small farmers could assist on **reducing energy use on farm level** and **adopting earlier** newer, more energy efficient technologies and renewable energy systems.
- In-depth research into the **relationship between farming system, farm size, geographical location and energy use** is required, with special attention in the impact of **shifting to non-conventional systems** (organic, conservation) that does not necessarily mean that energy use will be reduced.
- Another very important topic of research would be the development of a **common methodology for on farm energy audits** in a Life Cycle Assessment format to calculate the total yearly energy consumption of all types of farms in different pedoclimatic conditions.

3.1.2. Specific Research Ideas

This work has produced a series of specific research ideas from the missing information found in literature:

3.1.2.1. Open-field agriculture

- Research on **how to reduce chemical fertiliser** (mainly nitrogen) **use in farms** (its production and use accounts for about 50% of total energy use) is necessary either by optimising application rate spatially and temporarily using **precision techniques** or by substituting them with **nutrient carriers of biological origin**.
- Research on **conservation agriculture** impact on energy (directly and indirectly) should be enforced for different pedoclimatic conditions across Europe.
- Research on the **reduction of pesticides** (which accounts for 5% of the total energy inputs), could be achieved by minimising the consumption of manufactured pesticides, increasing their use

efficiencies, transitioning to more sustainable production systems, and increasing the share of locally produced organic pesticides.

- Research on **efficient tractor/implement combinations**, switching to **tractors powered by on-farm produced RES** (e.g., biofuels like biomethane from manure and waste residues or locally produced electricity from RES) could have a large impact on overall diesel use.

3.1.2.2. Greenhouses

- There is relatively little data and few studies that have looked at energy use in greenhouses in the EU. As such our findings are limited to several countries and crops and highlights the importance of further research into **energy use of different types of greenhouses for all important crop types under greenhouses.**
- There seems to be several data inconsistencies, for example, the annual published greenhouse energy monitor for the Netherlands states that heating accounts for around three quarters of all energy inputs and other energy inputs around a quarter. However, most LCAs covered in this study suggest that heating/cooling accounts for up to 99% of all energy inputs. This **discrepancy needs further research**.
- For high tech greenhouses, research should be increased on **innovative heating systems using sustainable sources of heat** (e.g., geothermal, biomass) and a special interest in **heat pumps** for combined HVAC should be given to shift from fossil fuels to electricity increasing efficiency and renewability through RES derived electricity (possibly locally produced).
- Research regarding low tech greenhouses should mainly focus on **agricultural input (fertilisers, pesticides, water) reduction** to decrease their energy profile, as in open-field agriculture.

3.1.2.3. Livestock

- Research to reduce the use of **animal feed** is vital for energy (indirect) use decline in EU agriculture. Special interest should be given to the energetic and environmental **impact calculation of local vs imported** protein content animal feed and the **substitution with locally produced high protein feed**.
- Research on **alternative feedstocks for feed**, such as bakery products, green biomass (glass/clover), insects, micro-algae and single cell proteins – for pig and poultry farming that would reduce the environmental footprint of animal feed[1].
- Research on **heat pumps for combined HVAC** should be prioritised to shift from fossil fuels to electricity increasing efficiency and renewability through RES derived electricity (possibly locally produced).

3.2. Regional Workshops

The central tool for information exchange in the regional hubs was the three multi-actor workshops per hub, bringing together research, extension, industry and farmers within and outside the AgroFossilFree project. Twenty-four multi-actor workshops were conducted in total covering the Northern, Western, Southern and Central/Eastern regions of Europe. The workshops captured stakeholder's innovation research ideas on a regional level.

Based on the guidelines (see Deliverable 3.3.), several FEFTS were presented at the starting point of the workshops to initiate discussion. The list of FEFTS presented reflects across themes (open-field, greenhouses, livestock), covering all RES for agricultural use (i.e., biomass, solar energy, wind energy,

[1] EIP-AGRI Focus Group. 2020. "New Feed for Pigs and Poultry Final Report.

geothermal energy), alternative power supply for agricultural vehicles (i.e., biofuels, electrification), storage of excess energy (i.e., as fuel, as heat, or as electricity) and HVAC solutions (i.e., heat pumps, biomass boiler, CHPs, BMSs). Tools to measure and guide operations, as well as management tools for agricultural practices and input application which are constantly based on the latest knowledge, are also common topics across the three themes. Conservation agriculture related FEFTS were also shown to participants. Combined or complete systems for efficient heating/cooling, lightning, and ventilation were also presented for greenhouse and livestock farming.

After this presentation, the discussion between stakeholders was initiated with a certain series of questions. Of which some were about research ideas. The analysis regarding the research recommendations derived by this conversation is sorted by themes and can be found in detail in Deliverable 3.3.

3.2.1. Open-field agriculture

The main research topics to increase FEFTS adoption in European open-field farming are given below:

- Further research on **precision agriculture** (e.g., decision-support systems, efficient irrigation systems, precise fertilisers application, smart pesticide application, machinery digitalization, controlled traffic farming to reduce machinery movement within and between farm plots)
- **Alternative types of fuels from different sources than fossil** (i.e., biomethane from biogas upgrading, wet pyrolysis for bio-oil. GTL from biogas to existing diesel engines, production of NH_3 to be used as fuel or for fertiliser, and the potential in recycling biomass for fuels).
- More research on **2nd and 3rd generation biofuels** to reach commercial level.
- Increase **conversion efficiency of biomass or solar/wind into fuel** to avoid energy loss.
- Develop **agricultural machinery based on alternative fuels or electric** and investigate their in-field performance.
- Develop **models in easy-to-use formats** to calculate the right sizing in machinery and the right energy carrier, based on the farm size.
- Agricultural machinery analysis and decision support to **reduce idle effects** to consumption that can reach 20% of tractor uptime, **optimise driving patterns** and field/road transport (maximum operating time, minimum operational disturbances).
- Use of **robotics to substitute operations** for which there is labour (-skills) scarcity and/or repetitive, less time constrained operations.
- Optimise **battery technology** and **incorporation of photovoltaics** in agricultural **robots**.
- Studies on the **GHG impact of different machinery technologies**.
- **Conservation agriculture research** in different crop types and pedoclimatic conditions to measure the impact for several consecutive years.
- **Niche and existing crop rotation systems** should be investigated in terms of how effective they are in reducing direct (fuel) and indirect (fertilisers, pesticides, water) energy use. Decisions on crop rotation systems should take into account the effect on soil CO_2 sequestration and co-benefits.
- Research on the soil with focus on **soil living entity** to generate knowledge about the biological fertility of the soil and how to use microbiology to work for crop cultivation without destroying the soil, reducing fertilisation needs.
- Research on **crop varieties adapted to local conditions** (low need for nutrients, water and crop protection), better able to adapt to changing climatic conditions.

- The problem of **natural fertilisers' distribution** could be solved with technologies for drying fertilisers or processing them. Analysis of their transport over long distances should be also included.
- Large in-field experimentation on the impact of **nitrification inhibitors** on CO_2 reduction from agriculture is of high importance, as the indications show a significant impact.
- **Green certificates enhancement** with better databases.
- There are doubts that a **CO_2 tax** will support a green transition towards FEFTS adoption, so research need to be used to **validate this.**
- Studies on the importance of land/field location distribution concerning all parameters for **saving fuel/transport/logistics**.
- Document **accurate data** (document consumption of fossil and non-fossil fuels) that identify points of intervention where significant energy use occurs.
- **Bio-char production** research for soil enhancement.
- Investigation of **local hydrogen production**, in terms of technological maturity, but also regarding distribution and practical application in farms.
- Optimise **hydrogen production lines** from hydrolysis using excessive electricity from RES installed in farms during the day.
- Optimise **chemical fertilisers' production lines** to reduce the related energy and GHG emissions.
- Review and collect research around FEFTS in open-field agriculture to create an overview of research, as it is difficult to find out where to start with projects.
- Design research programs that take into account how to compensate farmers from a time dedication perspective.
- Collaboration between energy and agricultural research program schemes.

3.2.2. Livestock

The main research topics to increase FEFTS adoption in European livestock farming are given below:

- **Biogas production** using **animal faeces** (in the framework of circular management of farm waste) or **combinations with specific crops or crop residues** for CHP solutions or biomethane upgrading for injection into natural gas pipelines or direct use in farm's vehicles as fuel.
- **Qualitative analysis of existing and novel animal feed types** must be conducted to reduce their energy requirement to be produced.
- **HVAC specifically for livestock buildings** should be developed to consider the characteristics of high population, dust, and gases.
- Research and showcase the **use of heat pumps in different livestock facilities**. Identify how to increase supply temperature to heat pumps. Identify how to improve Coefficient of Performance (COP) of heat pumps. Need studies of how heat pump performs under different flow temperatures and outside temperatures (air to water heat pumps) and its potential for cooling.
- **Ground source heat pumps (GSHP)** should be researched as a solution for livestock facilities combined with mapping of areas that have the requisite underground heat. Research on the combination of GSHP with other renewables from an agricultural perspective.
- **Geothermal suitability maps** should be developed for the EU member states that do not have them easily available.
- Need for **'proof of concept' flagship projects** to demonstrate the different applications of geothermal/heat pump technologies and their benefits in dairy, pig and poultry farming.

- Design **fossil energy free livestock farms (in all types)** and run experiments to optimse the combination of FEFTS needed.
- Develop **new vehicles' driving modes** within a livestock facility to reduce fuel consumption.
- Investigate needs for increased **deployment of robotic systems** within the livestock facility for feeding or transporting material.
- Environmentally friendly design of agricultural production processes with **increased automation and electrification** of machines and systems and use of **self-produced energy from RES**.
- **Regional decentralized and intelligent energy distribution** among farms and local settlements to improve integration of RES.
- Use of **pyrolysis as a manure treatment** technology, especially the effect on soil and nutrient utilization after treatment.
- Develop **certification and verification systems** for different types of FEFTS applied in livestock farms.
- Research different engineering solutions involving CHP, solar, heat pumps, gas boiler, water storage, ground thermal, CO_2 extraction and seasonal storage options.
- Research on **electric or hydrogen powered vehicles** development and technoeconomic analysis of their implementation based on local circumstances and financial situation.
- **New hybrids of animals** (DNA improvement) for allowing higher productivity for indirect energy use efficiency improvement.
- How to combine heating and cooling to cut the cost of production. Research on developing simple control systems and off-season storage options.
- Farmers should be included in techno-scientific research programs as partners or other ways of official involvement, because today projects are designed regarding insights leverage, which may be created upon the hypothesis that farmers will be free of burdens to attend, respond, or collaborate with research organizations. This way research will stop being a burden for farmers.
- Design research programs that consider how to compensate farmers from a time dedication perspective.

3.2.3. Greenhouses

The main research topics to increase FEFTS adoption in European livestock farming are given below:

- Optimise **semi-transparent photovoltaics** and **storage through batteries** in different greenhouse and crop types.
- Application of semi-transparent agrivoltaics to research the result on **crop and energy productivity**.
- Research on **precision agriculture**, automations and IoT technologies application in greenhouses.
- Incorporation of **energy management systems** into existing automation systems of greenhouses.
- Use of **agricultural waste** from greenhouse production for biofertilisers, heat and/or electricity.
- **Straw use** for heating systems in greenhouses.
- **Pyrolysis of biomass** to heat greenhouses and produce biochar as soil amendment.
- **Anaerobic digestion** of agricultural by products from greenhouses.
- Investigate the **use of poultry manure** (dried) as a fuel in woodchip boilers.
- Conduct research on additional sources of wood fuel and develop supply chains. Simple boiler systems must be **reliable with alternative fuels**.
- Demonstrate how **biomass energy systems fit in** with older greenhouses and existing technologies.

- Investigate applications for **biochar**.
- **CO_2 extraction** from the atmosphere or neighbouring producers to feed greenhouses.
- **Green labelling** for greenhouse products derived from FEFTS integrated farms.
- **Humidity extraction** from greenhouses to optimise climatic conditions, dehumidify the building to avoid pests and collect clean water for other uses.
- Research on the financial possibilities of **different clean energy production and storage** in greenhouses by looking into existing business cases and what business cases can be created in the future with the infrastructure and technologies that are available.
- Develop **sustainable pricing models and markets** for energy crops.
- New technologies such as bioenergy with **carbon capture and storage** –securing geological storage sites.

3.3. Transnational Workshops

After the conclusion of the series of 24 Regional Innovation Workshops covering the 3 production systems of agriculture, namely open-field, greenhouses and livestock, 3 Transnational Innovation Workshops per theme were organized aiming to bring together relevant agricultural stakeholders to discuss about all the topics of AgroFossilFree, including research priorities to increase FEFTS adoption. The analysis regarding the research recommendations derived by this conversation is sorted by themes and can be found in detail in Deliverable 3.4.

3.3.1. Open-field agriculture

The main ideas for new research from the transnational workshop about open-field agriculture were:

- Further development of **precision agriculture and conservation agriculture** (standalone and in combination), as they can both offer the most in terms of fossil energy use reduction to those farmers who cannot afford investment in RES production technologies. Adapt both precision and conservation agriculture to national or even regional levels and apply demonstration/knowledge sharing.
- Energy research should be **closely related to field operations and the overall crop management** to identify the most important energy consuming practices and increase energy efficiency.
- **Soil carbon sequestration measurement** from different agricultural practices (conventional, organic, conservation, etc.) should be done in long experiments.
- **Agrivoltaics** should be researched in terms of agricultural and energy production (how much the one impacts the other) and provide optimum solutions, considering the disadvantage of agrivoltaics of trapping land for decades after installation in the field.
- **Alternative fuelled vehicles** should be further investigated in the context of rising fuel prices focusing on fuel production and consumption within the farm.
- **Biogas plants using alternative feedstock** from open-field agriculture (e.g., grass, residual straw) should be analysed. Questions to be answered would be how far it is possible to extent self-sufficiency of heat and electricity produced from biogas on a European level, and what will be the implications of this self-sufficiency.
- **Alternative agricultural strategies** (conservation, permaculture) should be analysed in terms of direct (fuel) and indirect (fertilisers, pesticides and water) energy reduction.
- Using **existing research results (e.g., on good crop rotation systems)** that is a lot easier to be adopted with low investments, could be the answer to a primer reduction of agricultural inputs (indirect energy) use, achieving significant results on energy consumption in agriculture.

- There is a need to **shift research to holistic projects** that look at the whole circular economy including the agricultural sector as a fully connected link of the value chain and discontinue the European research schemes that are mainly based on siloed projects.

3.3.2. Livestock

The main ideas for new research from the transnational workshop in livestock were:

- Research projects dealing with **biogas/biomethane production** and development of demonstrations and pilot farms to **test different feedstock types in real conditions**.
- Biogas/biomethane production was highlighted as the **most interesting research topic** because the technology is taking maximum CO_2 from atmosphere making manure valuable, it is an available source of renewable energy and handling manure in a climate friendly way, and because it can make a difference on impact on a relatively short term.
- **Biogas** research at **farmer or cooperative level**.
- Implementation of **small biogas plants on dairy farms**.
- Precision livestock technologies should be further investigated, especially about **feed reduction by timely provision of feed** to animals to reduce indirect energy consumption.
- Research on **recycling/resourcing of waste** (e.g., straw, bedding material) from animal production.
- Analyse energy consumption in **every supply chain step and operation** on livestock farms.
- Measure and analyse **energy input at dairy farms** and propose FEFTS to be integrated.
- Research should produce **assessments and economic KPIs for FEFTS** in different livestock farm types and give easy access to farmers.
- **Online training tool** development to teach advisors about FEFTS.
- Design **on farm fuel production and use** for tractors.
- Demonstration of **"carbon-free" livestock farms**.
- How to combine **agrivoltaics with electric tractors** for practical use.
- Design an **energy efficient and fully automated model sheep farm** of 1200-2000 ewes with low carbon footprint using state of art technology and machinery.
- **RES storage on farm** should be also investigated for remote livestock farm.
- Research how to **increase fodder yield**, while lowering energy consumption in the field by developing new technology.
- Utilise **data registration** of all practices in livestock farms for big data approached.
- **Under representation of small farms** in important research projects.
- **Breeding** could help increasing production efficiency, but regarding energy the impact is very subjective, based on all other practices of the farm hosting the new breed.
- Research should either be designed from scratch to **be aligned with regulation**, or an authority agreement should be given that the research is **intended to change the regulation**, when research results are published.
- European projects have the **advantage of knowledge transfer** from very advanced institutions to less advanced to grow FEFTS faster.
- **Social research** of the relevance of Biogas/Biomethane solutions for the society in general.
- A **complete Agricultural Knowledge Innovation System (AKIS)** with collaboration between farmers, contractors, advisors and universities is a major need for good research (e.g., Denmark and the Netherlands have well established AKIS).

- Research projects should focus on **gathering FEFTS knowledge and disseminate** to all EU countries, offering practical knowledge and demonstrations, and that multidisciplinary involvement is a key aspect for innovation.

3.3.3. Greenhouses

The main ideas for new research from the transnational workshop in greenhouses were:

- Research on **glass semi-transparent agrivoltaics** application with different PV module density and coatings to allow specific spectra range to measure the impact on different horticultural crops.
- Biomass systems for heating around the concept of circular economy, using **locally produced biomass**.
- **Precision agriculture** applied in greenhouses using **decision support systems** to reduce agricultural inputs.
- **Combined Heat and Power (CHP) systems using local energy sources** controlled by a **Building Management System (BMS)** to provide electricity for the greenhouse and sales of the excessive part to the grid with simultaneous heating of the building.
- **Geothermal heat pumps** research for different heat input combined with research on georeferencing all geothermal fields.
- Research on **nutrient and energy use inefficiency** and application of resources and materials **reuse**.
- **Combined use of various FEFTS** (RES for energy independency, precision agriculture for input reduction, alternative HVAC solutions for optimum climate control) to provide optimum agronomic and energy results for producers.
- Combined agronomic and energy research projects in a multidisciplinary format.
- Investigate **robotics for several activities in greenhouses** (e.g., harvesting robot arms, unmanned vehicles for yield transport in the greenhouse and the storage rooms, tethered drones for plant monitoring, etc.)
- Research collaborations: joining already established pan-EU networks to get support on technical issues, collaborate with different agricultural production systems other than greenhouses (livestock, industrial processes), create associations (private organisations), EU-China, EU - USA, EU - Africa, PhDs, joint events, pilot cases around the globe, enterprise information portal (EIP), COST projects, energy consumer associations, community energy projects, sustainable energy communities.

4. CONCLUSIONS

The above analysis of research topics that have been discussed and selected from the AgroFossilFree processes shows that even if FEFTS development in all directions (clean energy production, energy efficiency and soil carbon sequestration) is extensive and FEFTS solutions have reached the market for farmers to select and apply in their businesses, there are a lot of steps to be taken to reach the final goal of defossilisation of agriculture.

There are a number of key research ideas, in general and for specific sectors, that are proposed and highlighted by varying stakeholders (farmers, researchers, companies, advisors) time and again. The representatives of AgroFossilFree consider these to be of especially high priority:

General Research Recommendations:

- Farm Size and Unification: Investigate the impact of farm size on energy use and explore unification strategies for small holdings to adopt newer, more energy-efficient technologies.
- Farming System and Energy Use: Research the relationship between farming systems, farm size, geographical location, and energy use, considering the shift to non-conventional systems like organic and conservation agriculture.
- Methodology for Energy Audits: Develop a common methodology for on-farm energy audits in a Life Cycle Assessment format to calculate total yearly energy consumption for different farm types and conditions.

Open-Field Agriculture:

- Research ways to reduce chemical fertilizer use through precision techniques or biological nutrient carriers.
- Investigate the impact of conservation agriculture on energy use under different pedoclimatic conditions. Conduct long-term experiments on soil carbon sequestration under different agricultural practices.
- Explore methods to reduce pesticide use and transition to sustainable production systems.
- Research efficient tractor/implement combinations and on-farm renewable energy sources.
- Study the impact of robotics on labour-intensive farm operations.
- Analyse the importance of crop rotation systems on energy consumption.
- Develop precision agriculture and conservation agriculture further, adapting them to national or regional levels.

Livestock:

- Focus on biogas/biomethane production using animal waste and specific feedstock combinations. Assess the feasibility of small-scale biogas plants on dairy farms.
- Conduct qualitative analysis of animal feed types to reduce energy requirements.
- Develop HVAC systems tailored for livestock buildings.
- Further explore the use of heat pumps in various livestock facilities. Investigate ground source heat pumps and geothermal suitability mapping.
- Research alternative fuels for vehicles within livestock facilities.
- Develop certification and verification systems for FEFTS in livestock farms.

Greenhouses:

- Research the application of semi-transparent agrivoltaics and their impact on crop and energy productivity.
- Investigate biomass systems for heating in a circular economy context.
- Study precision agriculture, automation, and IoT technologies in greenhouses.
- Incorporate energy management systems into greenhouse automation.
- Explore the use of agricultural waste for biofertilizers, heat, or electricity.
- Investigate various heating solutions, such as straw and pyrolysis.
- Examine CO_2 extraction from the atmosphere for greenhouse use.
- Study humidity extraction and water collection from greenhouses.

The work carried out during AgroFossilFree highlighted many important areas and topics for future research ranging from research methodologies to relationships between different factors as well as specific strategies and technologies. The technological readiness level (TRL) of the above-mentioned research recommendations covers all range between low maturity and ready-to-use technologies that need to be adapted to agricultural environment. It seems that mature solutions should be investigated for farm level application in Innovation Action (IA) research projects to demonstrate them in real farms, optimise them and promote them for direct use to contribute in agricultural defossilisation in the near future. On the other hand, FEFTS of low maturity should become subject of Research and Innovation Action (RIA) research projects, where technology development can take place and increase the TRL of the selected FEFTS and make them candidates for future IA projects or direct funding from the private sector to develop commercial products.