Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT TEMPLATE

SECTION 1: PROJECT DETAILS – FOR PUBLICATION

Project Title	National Artificial Intelligent Dairy Energy Application (NAIDEA)
Lead Grantee (Organisation)	Munster Technological University
Lead Grantee (Name)	Dr. Michael D. Murphy
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	Name	**Organisation**
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Collaborators	Dr Eleanor Murphy Dr. Philip Shine	Bord Bia MTU

Project Summary (max 500 words)

Agriculture is the largest sectoral contributor to greenhouse gas emissions in Ireland, contributing to over three times the EU average. However, there currently exists conflicting government targets focusing on reducing emissions by 30% by 2030 and increasing the value of the Agri-foods sector by 85%. To achieve this, the government have targeted at least a 20% reduction in agricultural energy use and at least 20% deployment of renewable energy technologies by 2030, while focusing primarily on energy intensive farms.

This project focuses on the development of the National Artificial Intelligent Dairy Energy Application (NAIDEA), which will bridge the gap between Ireland's population of dairy farmers and national policy related decision making. The current state of the art, Agricultural Energy Optimisation Platform (AEOP) currently relies upon individual farmers to investigate and upgrade their energy infrastructure. This limitation will be removed through the development of NAIDEA, which will integrate macro-level survey information collected as part of Bord Bia's Sustainable Dairy Assurance Scheme, with advanced machine learning technologies. NAIDEA will efficiently and cost effectively quantify the energy related carbon footprint of milk production, while also identifying energy intensive dairy farms that can be directly targeted for energy improvements.

This project had three primary components: 1) constructing an energy questionnaire for integration with Bord Bia's national survey carried out on Ireland's population of dairy farms. 2) the development and validation of machine learning models to predict total, milk cooling, milk harvesting and water heating electricity consumption, and 3) develop NAIDEA's graphic user interface (GUI) and standalone executable for installation and usage of NAIDEA on any workstation.

Model development involved algorithm selection, feature selection, hyper-parameter tuning and nested cross-validation using data collected on 84 dairy farms between 2014 and 2021. Artificial neural networks, decision trees, ensembles forests, and support vector machine ML models were assessed. The artificial neural network was determined to be the most suitable algorithm for NAIDEA's backend, due to its high prediction accuracy and robust predictions. Within NAIDEA's backend, a five-point energy rating was developed to rate farms from A (highly efficient) to E (highly inefficient) based on each farm's forecasted electricity consumption per litre of milk, while accounting for solar PV energy generation. GUI development employed Python and PyQt5, a powerful Python package for developing GUIs. NAIDEA's GUI is composed of five sections: i) import/export data, ii) filtering, iii) macro-level statistics, iv) farm-level data and v) help section. The macro-level statistics section displays user friendly charts related to the infrastructural, energy, and carbon emissions breakdown of farms which fall within the selected parameters within the filtering section. In addition, all charts and the processed database can easily be exported as image or text files, respectively.

Consistent communication with key stakeholders has allowed NAIDEA to be tailored towards the requirements of its expected end users. This involved multiple testing and feedback rounds to develop a final tool. NAIDEA is available at: https://doi.org/10.5281/zenodo.6511392.

Keywords (min 3 and max 10)	Energy in agriculture, energy optimisation, energy simulation, researched informed policy, sustainable food production.

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATIOI (max 10 pages)

2.1 Executive Summary

This project focused on the development of a National Artificial Intelligent Dairy Energy Application (NAIDEA). NAIDEA is a desktop application that integrates macro-level survey information collected throughout Ireland's population of dairy farms, with advanced machine learning models. In Ireland, agriculture is the largest sectoral contributor to greenhouse gas emission, contributing to over three times the EU average. However, there currently exists conflicting Irish government targets focusing on reducing emissions by 30% by 2030 and increasing the value of the Agri-foods sector by 85%. To help achieve these conflicting targets, the government have targeted at least a 20% reduction in agricultural energy use and at least 20% deployment of renewable energy technologies by 2030, while focusing primarily on energy intensive farms [1]. NAIDEA can provide government bodies and relevant stakeholders with key performance indicators related to the trajectory of Ireland's dairy sector in relation to energy use, while enabling a targeted approach to identify energy inefficient dairy farms.

The first phase of the project developed an energy questionnaire for integration with national surveys carried out as part of Bord Bia's Sustainable Dairy Assurance Scheme. This energy component allowed for farm-specific details collected on a national scale, to be later inputted into developed and validated machine-learning models for generating key performance indicators and energy reports.

The second phase involved the development and validation of machine learning based models for predicting electrical energy consumption on Ireland's population of dairy farms. Model training was carried out using data collected between 2014 and 2021 via a remote monitoring system installed on a cohort of 80+ Irish commercial dairy farms. Model development involved assessing multiple machine learning algorithms including artificial neural networks (ANN), decision trees, ensembles forests, and support vector machines in conjunction with 1) multiple farm parameter subsets, 2) hyper-parameter tuning, 3) outlier detection and 4) nested cross-validation to develop models that generalised well across Ireland's population of dairy farms.

The final phase of the project involved the development of the final standalone application that can be easily downloaded and installed on any workstation. NAIDEA allows for data (such as Bord Bia's survey data) to be easily imported, where total, milk cooling, milk harvesting, and water heating electricity consumption can be predicted for each individual farm.

Decision support tools are becoming increasingly important mechanisms for packaging complex scientific methods for end-users, helping to guide decision making. As such, NAIDEA provides government bodies and agri-stakeholders access to cutting edge decision support information.

Introduction

In 2015, government policy set out targets for increasing the overall output from Ireland's agricultural sector by 60% and related food exports by 85% [2]. Agriculture is Ireland's largest producer of GHG emissions, responsible for 37.5% of national output in 2021, compared to an average of 11% across EU-27 countries [3], [4]. Agricultural activities produce GHG emissions due to on-farm processes such as eccentric fermentation, fossil fuel energy use, agricultural soils management, manure management, liming and urea application. However, Irish policy makers have also set out targets for reducing agricultural related GHG emissions through their Climate Action Plan, and Ag-Climatise report.

The Climate Action Plan has set out a target to work towards a carbon-neutral Irish economy as a 'horizon point' for 2050, covering emissions related to agricultural activities as well as those related to electricity use/generation, transport, buildings, enterprise and services, and waste and the circular economy [5]. Within this Climate Action Plan, sets of counter measures aimed towards mitigating GHG emissions are identified for each sector of the economy, heavily referencing the Teagasc Greenhouse Gas Marginal Abatement Cost Curve (GHG MACC) report for mitigation strategies related to agricultural related emissions [6]. The Teagasc GHG MACC report quantified the extent of GHG reduction that can be achieved through cost-effective agricultural mitigation measures, categorised by agricultural mitigation, land-use mitigation, and energy mitigation strategies. This led to a GHG emissions reduction target of 22-30% by 2030, compared to 2005 levels being identified. As the global demand for dairy products is forecasted to increase by more than 66% by 2050 [7], reducing livestock numbers in Ireland would be counterintuitive from a global GHG emissions perspective, as dairy production is likely to be supplied from other, less sustainable regions. Coupled with this, reducing livestock numbers would have a largely negative effect on production and export targets, resulting in reduced employment and income for Irish agricultural stakeholders. Lanigan et al. [6] therefore suggested reducing agricultural related GHG emissions through the adoption of new technologies, favouring those technologies that can also increase financial productivity to improve the likelihood of adoption when compared to those which would negatively affect the farmer's income [8]. From an energy perspective, this view is evident in DAFM's Ag-Climatise report which outlines a Roadmap towards Climate Neutrality in the agricultural sector. This document outlines government targets to achieve a 20% reduction in agricultural energy use by 2030 across all farms in addition to generating at least 20% energy use from renewable energy sources while focusing primarily on energy intensive farming systems [1].

Farmers are therefore required to produce greater volumes of milk and/or manage greater numbers of livestock while producing less GHG emissions, while at the same required to prepare for potential periods of reduced income. This highlights the importance of offering decision support to agri-stakeholders looking to manage increasing livestock numbers both environmentally and cost efficiently. AEOP was developed to help tackle this problem. AEOP is an online platform, providing agricultural stakeholders with comprehensive information and advice relating to energy use, electricity costs, carbon emissions, renewable energy potential and on-farm technology investments. For its effective application, AEOP relies upon the individual farmers to use the platform and investigate the monetary and environmental impact of potential infrastructural upgrades. NAIDEA removes this barrier through integrating macro-level survey information collected as part of Bord Bia's Sustainable Dairy Assurance Scheme, with advanced machine learning technologies to continuously provide detailed analyses related to the carbon footprint of milk production, and the ability to identify energy intensive dairy farms requiring intervention.

NAIDEA efficiently and cost effectively quantifies the carbon footprint of milk production over time in conjunction with national surveys, while allowing government bodies to easily identify dairy farms which are consuming energy inefficiently allowing for targeted support mechanisms to be put in place. NAIDEA also provides Irish policy makers and researchers access to cutting edge research outputs and next generation energy simulation tools. These tools provide direct guidance and support to policy makers regarding the optimal utilisation of energy technologies. For example, NAIDEA allows for dairy farms consuming energy inefficiently to be identified, thereby allowing for a targeted, top-down approach to decarbonising Ireland's dairy industry with respect to energy use.

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The objectives of this project were to:

1) Update existing national surveys:
2) Model development and validation
3) Develop centralised application
4) Final system testing and validation
5) Dissemination, promotion and engagement

NAIDEA has leveraged over 10 years of scientific research carried out by Teagasc and Cork Institute of Technology/Munster Technological University based researchers. NAIDEA was developed to enable agri-stakeholders take advantage of the above-mentioned machine learning models and additional functionality. The development of NAIDEA was underpinned by five aims that focused on delivering a finished product that included: i) a simple installation process, ii) an intuitive and user-friendly interface, iii) import and export functionality, iv) the ability to quantify each farm's electrical energy use in relation to the mean, and v) a filtering mechanism to allow end-users to customize outputs in relation to installed infrastructural equipment, and farm size. NAIDEA's graphic user interface (GUI) was designed and developed using Python (version 3.8) and it's PyQt5 (version 5.15.6) package [9].

NAIDEA provides agricultural stakeholders:

1) Access to state-of-the-art machine learning models for quantifying total, milk cooling, milk harvesting, and water heating related electrical energy consumption, through an easy to use, intuited user interface.
2) A filtering mechanism whereby users may select and/or deselect a subset of dairy farms based on each farm's installed infrastructural equipment such as the type of milk cooling system, whether a variable speed drive was installed, and whether a plate cooler was installed for milk pre-cooling. In addition, the imported dataset could also be filtered according to herd size, and energy efficiency.
3) The ability to identify dairy farms consuming electrical energy inefficiently. An energy rating system was developed to allow NAIDEA users intuitively assess each dairy farm's total electrical energy consumption efficiency (Wh/litre) in relation to the population mean. The rating system consisted of a five-point scale from A to E, whereby a rating of 'A' represented those farms with the least electricity consumption per litre, a rating of 'C' represented mean efficiency, and a rating of 'E' represented the largest electricity consumption per litre category. Minimum and maximum rating limits band limits were determined using monitored total electricity consumption data.
4) The ability to calculate and monitor dairy energy related key performance indicators (KPI) over time. KPIs can be calculate over time at low-cost, without the use of specialised equipment to calculate the effectiveness of changes to government policy.

Project Outcomes

The following section highlights key outcomes from this project.

Updating of national surveys

An energy survey component was developed and integrated into Bord Bia's farm sustainability survey, to collate specific farm details that could later be used as input parameters to developed and validated machine-learning models. The optimum farm parameters were identified via model development and data mining methodologies. In total, 17 dairy energy related questions were identified to capture all farm parameters necessary to predict on-farm energy use as well as renewable energy and energy efficient technology uptake information allowing government bodies to quantify the impact of policy decisions over time. These questions include (but are not limited to): the renewable energy capacity installed on farm (solar PV, wind turbine, and/or solar thermal), use of energy efficient technologies (low-energy lighting, heat recovery, 100% green electricity), whether a variable speed drive is installed, as well as water heating energy source. The full list of information collected through the farm sustainability survey is shown in Table 1. This information is in addition to herd size and milk production figures retrieved separately through individual milk processors. Continually carried out on an ongoing basis, the resulting database allows government bodies to firstly assess the impact of policy measures on renewable energy and energy efficient technology uptake over time and secondly, easily generate energy reports for Ireland's population of dairy farms. Thereby allowing government bodies to identify those inefficient farms that require intervention and directing those farms towards reliable decision support information.

Table 1 Energy related survey questions

Description	Data Type	Unit
Renewable energy systems (solar thermal | solar PV | wind)	Numeric	m^2 | kWp | kWp
Capacity of battery storage	Numeric	kWh
Use of low energy lighting	Categorical	Yes | No
Use of night rate electricity tariff	Categorical	Yes | No
Whether heat recovery system is installed	Categorical	Yes | No
Use of green electricity tariff	Categorical	Yes | No
Number of parlour units	Numeric	n
Frequency of hot washing	Categorical	n/a
Type of milk pump	Categorical	n/a
Vacuum pump power	Numeric	kW
Variable speed drive in place	Categorical	Yes | No
Total bulk tank capacity	Numeric	litres
Water heating system power rating	Numeric	kW
Hot water tank capacity	Numeric	litres
Milk cooling system (direct expansion | ice bank)	Categorical	Yes | No
Milk pre-cooling (ground water | ice cold water)	Categorical	Yes | No
Water heating source (electric | electric & oil | oil | gas)	Categorical	Yes | No

Model development and validation

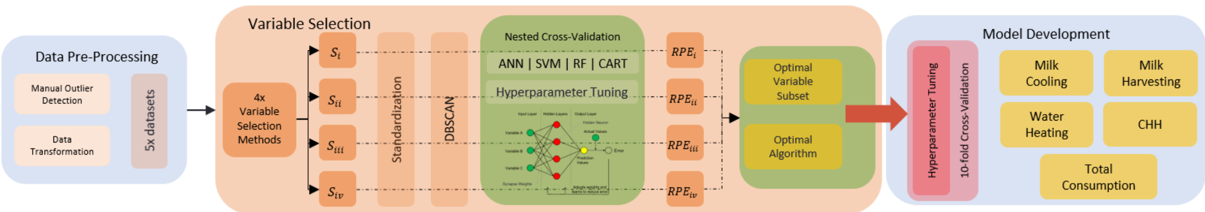

Figure 1 Model development and validation workflow

A model development and validation architecture was developed to train and test NAIDEA's machine learning models, as shown in Figure 1. This architecture allowed for the modular incorporation of a range of self-learning AI algorithms such as ANNs, decision trees, ensembles forests, and support vector machines. In addition, the architecture also incorporated machine learning methodologies including feature selection, hyper-parameter tuning, outlier detection and nested cross-validation all aimed towards developing an accurate model that could generalise Ireland's population of dairy farms. The ANN was determined as the most suitable algorithm for NAIDEA's backend due to its high prediction accuracy, generalisation capability and portability.

Table 2 Monthly prediction accuracy of total, milk cooling, milk harvesting, water heating and CHH models

Dependent Variable	RPE	CCC	r	RMSE	MAPE	MPE
i. Total	17%	0.95	0.96	359.87	14%	-3%
ii. Milk cooling	23%	0.94	0.95	167.67	31%	-17%
iii. Milk harvesting	22%	0.90	0.90	93.14	21%	-7%

iv. Water heating	34%	0.90	0.90	155.25	48%	-27%
v. CHH	15%	0.96	0.97	236.75	20%	-9%

CHH = Cooling, Harvesting and water Heating consumption

Monthly prediction accuracies of the five ANN models, as calculated using out-of-sample prediction values generated through 10-fold cross-validation are shown in Table 2. The CHH model (combined prediction of cooling, harvesting and water heating consumption) had the greatest prediction accuracy, with a resulting RPE value equal to 15%, and CCC value of 0.96. However, when considering MAPE (14%) and MPE (-3%) performance metrics, the ANN model predicting total electricity consumption had the greatest prediction accuracy. When predicting the individual components of the CHH consumption, model accuracy was considerably lower with RPE values of 23%, 22% and 34%, when predicting milk cooling, milk harvesting and water heating, respectively.

Table 3 Farm-level energy rating classification accuracy

Accuracy	Recall	Specificity	PPV	F_1 score	Cohen's K
95%	96%	98%	95%	95%	0.83

Recall = Sensitivity; PPV = Positive Predictive Value or Precision; Cohen's K = Cohen's kappa

A description of farm-level energy rating classification accuracy is shown in Table 3. Very high accuracy, recall, specificity, PPV and F_1 scores were calculated with all values greater or equal to 95% suggesting high classification performance. In relative terms, Cohen's K had the lowest performance metric value equalling 0.83. However, a Cohen's K value greater than 0.81 was considered as a near perfect agreement [10], [11]. These classification results clearly indicated the capability of the energy rating as a diagnostic mechanism for distinguishing between high and low electrical energy consumers throughout Ireland's dairy farms.

Develop centralised application

NAIDEA was developed using Python, a powerful object-oriented programming language, and is packaged as a standalone executable (.exe) file that can be easily downloaded to install NAIDEA on any laptop or workstation. NAIDEA allows for data (such as Bord Bia's survey data) to be easily imported, where total, milk cooling, milk harvesting, and water heating electricity consumption is autonomously predicted for each unique farm. Each farm is given an energy rating from A (highly efficient) to E (highly inefficient) based on each farm's simulated electricity consumption per litre of milk, accounting for renewable energy generation from sources such as solar PV. Specific electricity consumption per litre (Wh/Litre) limits (minimum and/or maximum), for each of the five energy rating categories are shown in Table 4, in addition to the proportion of study farms within each category. NAIDEA is currently deployed and available at: https://doi.org/10.5281/zenodo.6511392.

Table 4 Energy rating limits and the proportion of monitored farms within each category

Energy Rating	A	B	C	D	E
Limits (Wh/Litre) *	< 23	23 - 36	36 - 49	49 - 62	62 >
Proportion of dataset	4.9%	24.6%	41.0%	21.3%	8.2%

Wh = Watt-hours * Limits were calculated using dairy farms with no domestic energy use bundled with farm consumption (n=61)

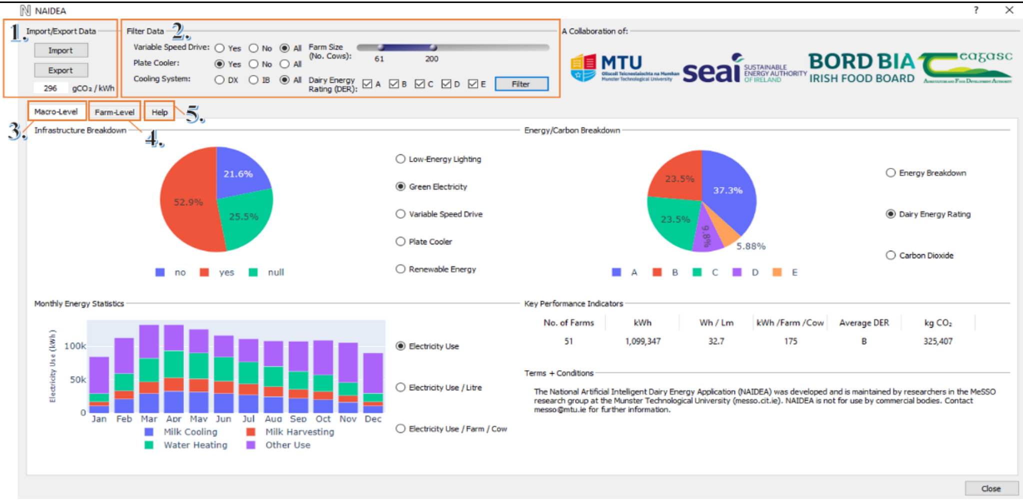

Figure 2 NAIDEA's macro-level section user interface

Macro-level Dairy Energy Reporting

NAIDEA's GUI has five primary components including:

1) An import/export section, that allowed users to import data (.csv) required for generating energy predictions using five pre-trained ANN models, export the processed dataset and results including farm-level energy ratings as well as input a carbon intensity value (gCO_2/kWh) to ensure carbon emission calculations are always up to date. The positioning of this section is shown via label 1 in Figure 2.

2) A filtering section whereby users may select and/or deselect a subset of dairy farms based on each farm's installed infrastructural equipment such as the type of milk cooling system (direct expansion (DX) or ice bank (IB)), whether a variable speed drive was installed (yes or no), and whether a plate cooler was installed for milk pre-cooling (yes or no). In addition, the imported dataset could also be filtered according to herd size (the total number of dry and lactating dairy cows), and energy rating (A to E). The positioning of this section is shown via label 2 in Figure 2, with a closeup shown in Figure 3.

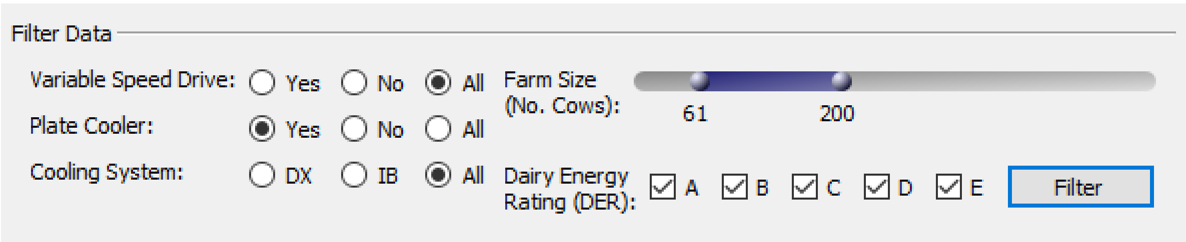

Figure 3 NAIDEA's data filtering component

3) A macro-level statistics section comprised of five sub-sections containing charts and figures resulting from the imported dataset and filter section parameters. These sub-sections were: *infrastructural breakdown*, *energy/carbon breakdown*, *monthly energy statistics*, *key performance indicators* (KPIs), and *terms and conditions.* The infrastructural breakdown sub-section allowed users to generate pie charts relating to the utilization of low-energy lighting, "green" electricity, variable speed drives, plate coolers and renewable energy technologies. A closeup of the infrastructural breakdown sub-section shown in Figure 4. The energy/carbon breakdown sub-section allowed users to generate pie-charts relating to the electrical energy use and energy-related carbon emissions of each major electricity consuming process on the

dairy farm (e.g. milk cooling, milk harvesting and water heating). In addition, the distribution of calculated energy ratings amongst the selection of farms may also be displayed as a pie chart. The monthly energy statistics consisted of a stacked bar chart that displayed mean electricity consumption (kWh), electricity consumption per litre (Wh/Litre) or electricity consumption per dairy cow (kWh/cow). The KPIs sub-section displayed a table consisting of the number of selected farms (as per filtering parameters), the cumulative electricity consumption, electricity consumption per litre (Wh/Litre), electricity consumption per dairy cow (kWh/cow), the mean energy rating, and quantity of energy related carbon emissions (kg CO_2). A closeup of the KPI table is shown in Figure 5. Lastly, a sub-section presenting NAIDEA terms and conditions is also displayed.

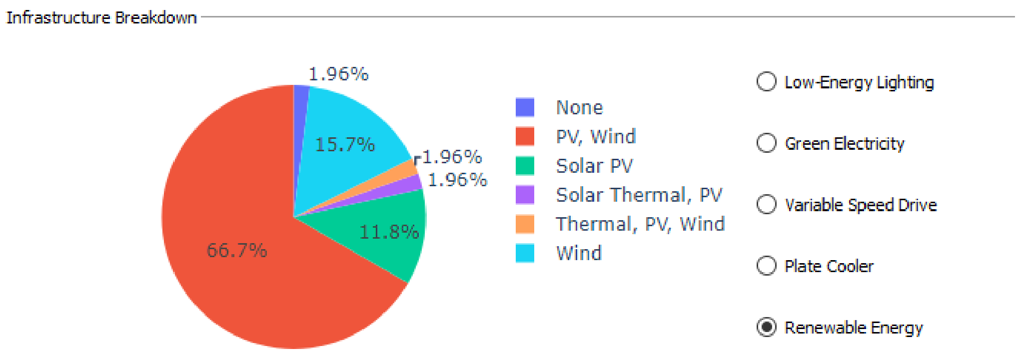

Figure 4 NAIDEA's infrastructural breakdown sub-section

Key Performance Indicators

No. of Farms	kWh	Wh / Lm	kWh /Farm /Cow	Average DER	kg CO_2
51	1,099,347	32.7	175	B	325,407

Figure 5 NAIDEA's key performance indicator sub-section

4) A farm-level data section contained the processed dataset (as per selected filter parameters) in tabular form containing all farm-level raw data used to populate charts and figures displayed in the macro-level statistics section. These data include a unique farm identifier, energy rating, herd size, milk production, capacity of renewable energy generation, etc... The farm-level section can be accessed via label 4 in Figure 2.

5) A help section presented a user manual to provide key instructional information to users on how to best utilize NAIDEA. The help section can be accessed via label 5 in Figure 2.

2.2 Project Impact

In 2020, Irish GHG emissions were 7% less than 2005 levels, far less than the initial target of 20%. Focus now turns towards 2030 where the Irish government has pledged to reduce overall GHG emissions by 30% compared to 2005 levels [12]. In 2021, the agricultural sector and energy industry were responsible for 37.5% and 16.7% of overall GHG emissions, respectively [13]. NAIDEA therefore has a direct impact on Ireland's long-term objective of transitioning towards a carbon neural economy by 2050, by focusing on the two largest GHG emitting sectors [5].

Continuous carbon footprint reporting and ensuring continual improvement will be crucial to the sustainable development of Ireland's dairy industry. In addition, implementing a targeted, top-down approach to decarbonising Ireland's dairy farms will be crucial to achieve Ireland's 2030 EU GHG emissions reduction targets. NAIDEA's development has been carried out with direct input from end-users and is currently having a direct impact on Bord Bia's farm sustainability survey. NAIDEA is currently being used directly by Bord Bia for energy reporting and to support decision making, by allowing Bord Bia to identify those Irish dairy farms who are producing milk inefficiently with regards to their energy consumption. Bord Bia are providing sustainability survey participants (dairy farms only) with energy reports incorporating their unique energy rating, farm-level recommendations to reduce fossil fuel use, and also directing these energy intensive dairy farms towards AEOP to identify the most suitable strategy that could be taken to improve energy efficiency and/or renewable energy generation on a farm-to-farm basis.

NAIDEA may also be utilised by government bodies to inform future policy to incentivise the uptake of energy technologies to improve energy efficiency and renewable energy production. In 2021, 8.75 billion litres of milk were produced in Ireland. Gaining even a modest reduction in the associated energy and environmental cost in producing dairy products on the farm side would result in considerable savings in overall energy consumption, production cost and carbon emissions. These savings would aid the industry in producing food in a cost efficient and environmentally sustainable manner, while also helping to maintain Ireland's green agricultural reputation.

NAIDEA will have a tangible impact on the Irish energy research community. NAIDEA is currently deployed and available to the wider scientific community for use and dissemination. Information relate to NAIDEA's correct utilisation and input data template has also been published. NAIDEA provides a cost efficient and reliable dairy energy reporting mechanism, forming the next step in minimising the carbon footprint of Ireland's dairy farms, closing the loop between energy intensive dairy farms and access to decision support information.

NAIDEA is also openly available to state agencies/government bodies to use for energy, environmental and economic analysis. The primary impact NAIDEA will make to enhancing Irish scientific competencies in this domain will be the artificial intelligent functionality, which will result in novel research findings and help Ireland to become a world leader in agricultural energy research.

Societal

NAIDEA provides dairy farmers (through Bord Bia) with an energy rating calculated based on their survey responses, milk production and herd size in addition to farm-level recommendations. Farmers can use this energy rating as a reference point for measuring energy farm-level improvement over time, in line with infrastructural upgrades, thereby driving sustainable development. This is expected to result in a substantial uptake in the deployment of state-of-the-art energy equipment. This proliferation in energy technologies will lead to improved energy efficiency and increased renewable production in turn leading to reduced energy costs and more environmentally friendly food production.

Responsible for 7.7% of national employment and 10% of total exports, the societal importance of the agricultural industry in Ireland is manifested in Ireland having the only sustainability programme (Origin Green) in the world operating on a national scale, uniting government, the private sector and food producers [14]. NAIDEA provides agri-stakeholders and government bodies and state agencies with the means of calculating the monetary, environmental and energy related impact of Irish dairy farming for sustainability reporting or marketing Irish dairy products abroad [2]. This monitoring allows for their continual improvement to be tracked, further strengthening Ireland's sustainable agricultural systems.

Economic

The abolishment of milk quotas in April 2015 resulted in a volatile milk pricing system, responsive to the supply and demand of milk and dairy products. In 2016 an average milk price decrease of 26% resulted in a 16% reduced average dairy farm income compared to 2015 [15]. Although 2021 milk prices have increased by 30% when compared to 2016, dairy farmers must still produce greater volumes of milk to remain competitive, while preparing for potential periods of reduced revenue while having less of an environmental impact. NAIDEA compliments the existing state of art dairy energy decision support tool, AEOP, through closing the loop between Ireland's population of dairy farmers and access to decision support information. AEOP provides farmers with decision support information to help alleviate some of this financial stress through calculating the long-term monetary impact of investing in energy efficient and renewable energy technologies on dairy farms. AEOP encourages farmers to become more energy independent, thereby reducing potential negative impacts of future increases in energy costs due to increased fuel costs or time-of-use and real-time-pricing tariff structures. The expected uptake in renewable technologies by Irish farmers will have a knock-on benefit to Irish energy companies, adding energy jobs to local economies and increasing the viability of small and medium energy businesses across Ireland. This increase in participation within rural economies will help to foster energy communities centring around local companies.

NAIDEA allows policy makers conduct a targeted approach to decarbonising Ireland's dairy industry, at a low-cost, without the use of specialised equipment. Through novel machine learning methodologies, NAIDEA is capable of forecasting farm-level electrical energy use using survey data and milk production and herd size data available from individual milk processors. Without NAIDEA, policy makers would require remote monitoring equipment to be installed and maintained on Ireland's population of 18,000 dairy farms, at a significant financial cost.

Technological

NAIDEA provides the Irish and international energy research community and policy makers with a tangible energy simulation tool, leveraging over ten years of scientific research in the agri-energy domain. NAIDEA packages complex data, machine learning based modelling in a functional and easily interpretable platform. All methodologies involved in the development of NAIDEA have been peer-reviewed in scientific journals, fortifying the evidence-based ethos employed throughout NAIDEA's development [16]–[18]. Open-sourcing NAIDEA removes any barriers surrounding access to decision support, thereby helping to maximise knowledge transfer and its positive impact on Ireland's agri-foods sector.

2.3 Recommendations

The final developed models that are embedded within NAIDEA's backend can only be utilized within the scope of the data used for model training. The ANN models were trained using data gathered via a remote monitoring system installed on a cohort of 80+ Irish pasture-based dairy farms each with herringbone milking systems. Thus, NAIDEA is not suitable for predicting energy use on farms that employ rotary, or robotic milking systems, or farms that operate a confinement based dairy system. Therefore, further work is required to expand the data collection mechanism in place to incorporate additional farming systems, thereby allowing for future empirical models covering these systems to be developed and embedded within NAIDEA's backend.

2.4 Conclusions and Next Steps

This report detailed background information, project outcomes and key impacts related to the development of the National Artificial Intelligent Dairy Energy Application (NAIDEA). NAIDEA was developed with a range of users in mind ranging from government bodies, policy makers and members of the scientific community, while consideration was given to balance advanced modelling software and user practicality. NAIDEA removes barriers relating to the optimal utilisation of the Agricultural Energy Optimisation Platform (AEOP) through integrating macro-level survey information collected as part of Bord Bia's Sustainable Dairy Assurance Scheme, with advanced machine-learning methodologies to identify farms that would benefit most from energy infrastructure upgrades. NAIDEA can efficiently and cost effectively quantify the energy related carbon footprint of milk production. NAIDEA also allows government bodies such as Bord Bia to firstly identify energy intensive dairy farms, and secondly, the ability to direct those inefficient dairy farms towards AEOP.

Future work will focus on furthering the decarbonisation of Ireland's agricultural industry through developing cognate tools for mapping the optimal pathways for renewable microgeneration on Irish farms, given significant updates to agri-energy policy in 2022/23.

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Note - Both Section 3 and Section 4 of this Final Report are required for SEAI review purposes only and will not be made publicly available.

SECTION 3: COMMUNICATION & DISSEMINATION (max 3 pages)

3.1 Communication, Dissemination and Exploitation

NAIDEA related methodologies and results were presented to members from the research community at six international, European, and national conferences over the duration of the project. These included the International symposium on climate-resilient agri-environmental systems (ISCRAES – virtual, Nov 2020), the 32nd Irish Environmental Researchers Colloquium (Environ – virtual, Oct 2020 and Belfast, June 2022), the international conference on Applied Energy (ICAE – virtual, Dec 2021), the ASABE Annual International Meeting (ASABE, Houston, July 2022), ISGT Europe 2022 (Serbia, Oct 22) and the ASABE Annual International Meeting (ASABE, Omaha, July 2023). This provided a useful avenue to 1) network with current users of AEOP, and 2) showcase NAIDEA methodologies and functionality to a wide range of members of the scientific community, how it is currently being employed by government bodies and complements the existing suite of agri-energy decision support tools.

NAIDEA methodologies were also disseminated to the national scientific audience and members of the public through an online webinar hosted as part of the Environmental Science Association of Ireland (ESAI) - Summer Webinar Series in 2020. NAIDEA was discussed under the following title 'Electricity use on Irish dairy farms-A national approach to improving efficiency using artificial intelligence' and involved a presentation and questions and answers section. Dissemination activities also included the development and publication of three peer-reviewed journal articles titled *"Over 20 Years of Machine Learning Applications on Dairy Farms: A Comprehensive Mapping Study"* (published in the *Sensors*) and *"Factors affecting energy efficiency in herringbone and rotary milking parlours" (Heliyon, in press)*. *Global Dairy Sector: Trends, Prospects, and Challenges* (published in Sustainability). Our work was also disseminated through one book chapter titled "*Tools and technologies to reduce fossil energy use on dairy farms"* which was written for publication in a book titled "*Energy-Smart Farming: Efficiency, Renewable Energy and Sustainability*" published by Burleigh Dodds in May 2022.

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3.2 Intellectual Property Management & Exploitation

The outputs from this project are a dairy farm infrastructure database, a centralised application, and multiple scientific and popular publications. Therefore, this project has generated no commercially applicable IP. The final outputs are available for the good of the Irish agri-sector and scientific community. The standalone executable file for installing NAIDEA has been made readily available, as it's source code for the good of the Irish research community.

Table 3.1 – List of Scientific Publications

Title	Main Author	Journal/Book/Proceedings Title	Date	Publisher	Year	Open Access	Peer-review
Predicting milk cooling, milk harvesting and water heating electricity use on dairy farms using artificial neural networks	Philip Shine	International Conference on Applied Energy	Jan – Nov 2021	Applied Energy Elsevier	2021	Yes	Yes
Over 20 Years of Machine Learning Applications on Dairy Farms: A Comprehensive Mapping Study	Philip Shine	Sensors	June – Dec 2021	MDPI	2022	Yes	Yes
Tools and technologies to reduce fossil energy use on dairy farms	Philip Shine	Energy-Smart Farming: Efficiency, Renewable Energy and Sustainability	Feb – August 2021	Burleigh Dodds Science Publishing Limited	2022	No	Yes
The development of a national-level energy assessment tool for the dairy industry	Philip Shine	ASABE AIM	Mar – May 2022	ASABE	2022	No	Yes
Factors affecting energy efficiency in herringbone and rotary milking parlours	Fergal Buckley	Heliyon	N/A	Elsevier	2023	Yes	Yes
Global Dairy Sector: Trends, Prospects, and Challenges	Michael Murphy	Sustainability	April 2022	MDPI	2022	Yes	Yes
Effect of milking efficiency, parlour utilization and herd size on the energy efficiency of Irish milking systems	Fergal Buckley	ASABE AIM	July 2023	ASABE	2023	No	Yes

Table 3.2 – List of Dissemination Activities (Michael D Murphy (MDM), Philip Shine (PS), John Upton (JU) Fergal Buckley (FB))

Type of Activity	Authors	Title	Date/Period	Location	Type of Audience*	Size of Audience
Conference Presentation	PS MDM	International Conference on Applied Energy 2021	30/11/21	Virtual	Scientific Community	40

Teagasc Open-day	JU	Online tools to help increase energy efficiency on dairy farms	14-16 Sept 2021	Moorepark/ Virtual	Farming community, Scientific Community	n/a
Journal Article	PS MDM	Over 20 Years of Machine Learning Applications on Dairy Farms: A Comprehensive Mapping Study	June – Dec 2021	Link	Scientific Community	3,369
Book Chapter	PS MDM JU	Tools and technologies to reduce fossil energy use on dairy farms	Feb – August 2021	Link	Scientific Community	n/a
Conference	PS	Environ 2022	22/06/22	Ulster University, Belfast	National Scientific Community	30
Conference	PS MDM	2022 ASABE Annual International Meeting	20/07/20	Houston, USA	International Scientific Community	30
Conference	PS	Environ 2020	21/10/20	Virtual	National Scientific Community	15
Conference	MDM	ISGT 2023	12/10/22	Novi Sad, Serbia	International Scientific Community	40
Conference	PS MDM	ISCRAES 2020	04/11/20	Virtual	International Scientific Community	25
User Manual	PS MDM	NAIDEA - User Manual	12/12/19	Link	NAIDEA Users	n/a
Application Deployment	MDM	NAIDEA – Application	02/05/20	Link	NAIDEA Users	162
Code Repository	PS MDM	Source code	05/08/2022	Link	NAIDEA Stakeholders	n/a
Webinar	PS	Electricity use on Irish dairy farms - A national approach to improving efficiency using artificial intelligence	16/07/20	Virtual: Link	National Scientific Community; Civil Society	72
News Article	MDM	CIT News Article	6/02/20	Link	Medias	n/a

Social Media	PS	Social media examples	2020 - 2022	Link1	Medias	n/a
Journal Article	FB MDM JU	Factors affecting energy efficiency in herringbone and rotary milking parlours	September 2023	Link (Pre-print)	Scientific community	n/a
Conference	FB MDM JU	Effect of milking efficiency, parlour utilization and herd size on the energy efficiency of Irish milking systems	July 2023	Link	International scientific community	n/a

SECTION 4: PROJECT STATUS & WORK PLAN

4.1 Work Plan

Please provide your list of work packages in Table 4.1 below, as detailed in your original Application Form, and include a status update for each.

Table 4.1 – List of Work Packages

No.	Title	Status Update and Completion Status (%)
WP1	Updating of national surveys	*100%*
WP2	Model development and validation	*100%*
WP3	Develop centralised application	*100%*
WP4	Final system testing and validation	*100%*
WP5	Dissemination, promotion and engagement	*100%*

In Table 4.2, please include details for each work package (copy and replicate the Table for each work package as required). Please provide an update on the progress, the specific milestones and deliverables achieved, and clearly identify any deviations from the original proposed work packages.

Table 4.2 – Summary of Work Packages

WP No. & Title	1. Updating of national surveys		
Start Month No.	1	**Finish Month No.**	6
WP Lead	Michael D. Murphy		
WP Contributors	Eleanor Murphy (Bord Bia), Nicola Rodgers (Bord Bia), John Upton (Teagasc), Philip Shine (MTU)		
Objective(s)	WP1-O1: Update dairy energy database		Completed
	WP1-O2: Identify important dairy farm parameters for AI model		Completed
Description (max 200 words)	The pre-existing database consisting of milk production, herd data, environmental data and energy data from a cohort of Irish dairy farms was updated to include data collected from 2019 onwards, for an additional 26 farms. This is a dynamic database that is continually updated autonomously as new data comes online. This database represents the largest and most comprehensive dairy energy database of its kind, allowing for key performance indicators and correlations to be updated and compared with previous years. As part of WP1, an energy component was developed and integrated into Bord Bia's survey, to collate specific farm details that can be later inputted into developed and validated machine-learning models (WP2). In addition, this energy component also collected renewable energy and energy efficient technology uptake information, allowing government bodies to quantify the impact of policy decision over time. The optimum farm parameters were identified via model development and data mining methodologies, using the aforementioned energy database. Bord Bia's national survey, carried out as part of Bord Bia's Sustainable Dairy Assurance Scheme was then updated to collect these dairy farm parameters.		
Milestones	WP1-M1: Integration of existing energy database with up-to-date data WP1-M2: Completion of data-mining methods		Completion Status: 100% Completion Status: 100%
Deliverables	WP1-D1: Complete energy database WP1-D2: Identification of easily attainable farm parameters to be collected as part of national surveys		Completion Status: 100% Completion Status: 100%

Deviations from planned WP (if applicable)			
Key Outcomes	Energy database Farm infrastructural and managerial processes database		

WP No. & Title	2. Model Development and Validation		
Start Month No.	6	**Finish Month No.**	13
WP Lead	Philip Shine (CIT)		
WP Contributors	Michael D. Murphy (MTU), John Upton (Teagasc)		
Objective(s)	WP2-O1: Identify the most suitable AI algorithm with up-to-date information		Completed
	WP2-O2: Development and validation of self-learning AI model		Completed
Description (max 200 words)	The development of the machine-learning modelling and validation architecture was completed. This allowed for machine-learning models for predicting total, milk cooling, milk harvesting and water heating, electrical energy consumption, and a combined forecast (milk cooling, milk harvesting and water heating), to be developed and validated. This was carried out using data from 84 dairy farms, collected between 2014 and 2021. Artificial neural networks, decision trees, ensembles forests, and support vector machines were assessed in conjunction with 1) multiple different farm parameter subsets, 2) hyper-parameter tuning, 3) outlier detection and 4) nested cross-validation to develop models that generalised well on Ireland's population of dairy farms. It was concluded that the artificial neural network algorithm was most suited for NAIDEA.		
Milestones	WP2-M1: Back-test wide range of AI algorithms using up to date information. WP2-M2: Develop AI model using optimum model hyper-parameters and farm parameters.		Completion Status: 100% Completion Status: 100%
Deliverables	WP2-D1: Final self-learning AI model		Completion Status: 100% Completion Status: 100%
Deviations from planned WP (if applicable)			
Key Outcomes	5x trained and validated machine learning models		

WP No. & Title	3. Develop centralised application		
Start Month No.	13	**Finish Month No.**	24
WP Lead	Michael D. Murphy		
WP Contributors	Philip Shine (MTU)		
Objective(s)	WP3-O1: Integrate developed model with autonomous energy reporting software		Completed
	WP3-O2: Combine national survey input data, self-learning AI model and energy reports to one system		Completed
	WP3-O3: Deploy system to centralised application using open-source application		Completed
Description (max 200 words)	NAIDEA was developed using Python, a powerful object-oriented programming language, and was packaged as a standalone executable (.exe) file that can be easily downloaded to install NAIDEA on any machine. NAIDEA allows for data (such		

	as Bord Bia's survey data) to be easily imported, and energy reports autonomously generated at the click of a button. Macro- and farm-level energy reports are generated, depicting infrastructural equipment breakdowns, energy and carbon breakdowns, monthly energy statistics and key performance indicators summarizing energy use in easy digestible form. To improve digestibility, each farm is given an energy rating from A (highly efficient) to E (highly inefficient) based on each farm's forecasted electricity consumption per litre of milk, accounting for renewable energy generation from sources such as solar PV. A filtering mechanism allows for farms with certain infrastructural equipment (such as plate coolers or VSDs), or within certain farm sizes or with certain energy ratings to be selected, and macro-level statistics calculated for comparative purposes. In addition, each generated chart can be easily exported as an image file, while the processed database (with calculated individual energy ratings) can also be easily exported. NAIDEA is deployed at: https://doi.org/10.5281/zenodo.6511392, where the standalone executable (.exe) file can be downloaded for installation of NAIDEA on any machine. In additional, a sample data file and legend are also available providing potential users with information related to correct input data type (i.e. numeric or categorical), and input data descriptions.	
Milestones	WP3-M1: Identify key energy reporting metrics WP3-M2: Present energy reports using easily digestible intuitive graphics and formatting WP3-M3: Integrate energy reporting software with national survey input data and AI model WP3-O4: Deploy centralised application	Completion Status: 100% Completion Status: 100% Completion Status: 100% Completion Status: 100%
Deliverables	WP3-D1: Easily digestible and functional energy reports structure WP3-D2: Comprehensive data stream from national survey to energy reporting WP3-D3: Centralised application (NAIDEA)	Completion Status: 100% Completion Status: 100% Completion Status: 100%
Deviations from planned WP (if applicable)	Originally, NAIDEA was planned to be developed using RStudio. However, Python was chosen due to its increased speed and functionality when developing standalone applications such as NAIDEA.	
Key Outcomes	A standalone executable file (.exe) allowing for NAIDEA to be installed on any machine	

WP No. & Title	4. Final System Testing and Feedback		
Start Month No.	17	**Finish Month No.**	30
WP Lead	Michael D. Murphy		
WP Contributors	Eleanor Murphy (Bord Bia), John Upton (Teagasc), Philip Shine (MTU), Nicola Rodgers (Bord Bia)		
Objective(s)	WP4-O1: Obtain feedback regarding NAIDEA performance from focus groups		Completed
	WP4-O2: Modify NAIDEA to ensure a highly effective user-friendly product		Completed
Description (max 200 words)	Prior to NAIDEA being officially deployed for national dairy energy reporting, there was an initial beta testing period with end used of the tool. This provided NAIDEA developers a vital opportunity to receive important feedback on NAIDEA's functionality. This was essential to ensure a smooth development and to minimize the potential for major revamp of the application. This was carried out through a consortium of stakeholders including state/semi-state bodies such as Bord Bia, Teagasc, in addition to members of the international agricultural scientific community. Once completed, a beta version of NAIDEA was sent to this consortium for testing and feedback. Firstly, this involved using NAIDEA with a synthetic database to identify functionality desired upgrades and changes, and secondly with real-world data to identify any potential bugs. Throughout the testing and feedback period, the consortium communicated with project developers directly with any concerns related to its functionality or limitations. NAIDEA was updated periodically		

	according to the responses from this consortium to help maximise NAIDEAs functionality, user friendliness and usability.	
Milestones	WP4-M1: Complete survey with stakeholders WP4-M2: Implement changes based on feedback from stakeholders	Completion Status: 100% Completion Status: 100%
Deliverables	WP4-D1: Improvement of NAIDEA based on feedback WP4-D2: NAIDEA completed and ready for use by stakeholders	Completion Status: 100% Completion Status: 100%
Deviations from planned WP (if applicable)	The testing and feedback period was shorter than was originally planned due to a delay in collection of Bord Bia's sustainability survey data. Data collection was delayed as Bord Bia expanded their accompanying documentation to ensure surveys were completed correctly. To ensure production was not delayed a s a result, a dummy database was developed to mimic the real-world survey data, and initial testing and feedback round carried out on these data.	
Key Outcomes	NAIDEA improved to end user's specifications	

WP No. & Title	5. Dissemination Promotion and Engagement		
Start Month No.	1	**Finish Month No.**	36
WP Lead	Michael D. Murphy		
WP Contributors	Eleanor Murphy (Bord Bia), John Upton (Teagasc), Philip Shine (MTU)		
Objective(s)	WP5-O1: Disseminated of project results through scientific publications		Completed
	WP5-O2: Direct engagement with key stakeholders and end users of NAIDEA		Completed
	WP5-O3: Wide scale promotion of Ireland's advanced dairy energy system		
Description (max 200 words)	The scientific outcomes of this project have been disseminated through six international, European, and national conferences over the duration of the project, two peer-reviewed journal articles and one peer reviewed book chapter. In addition, NAIDEA outputs were promoted at the Teagasc open-day, and an online webinar hosted by the Environmental Science Association of Ireland. Adoption of NADIA across the dairy sector has been achieved through its use by Teagasc and Bord Bia.		
Milestones	WP5-M1: Completion and submission of scientific papers WP5-M2: Presentation of findings at international and national conferences P5-M3: Promotion at seminars, workshops and conferences		Completion Status: 100% Completion Status: 100%
Deliverables	WP5-D1: Multiple journal papers and scientific article publications WP5-D2: Successful communion of project outcomes to key stakeholders WP5-D3: Adoption of NAIDEA across the dairy-sector		Completion Status: 100% Completion Status: 100%
Deviations from planned WP (if applicable)			

Key Outcomes	Multiple scientific publications Promotion of NAIDEA to scientific community Adoption of NAIDEA within Ireland's dairy industry