



Determinants of energy efficiency in the Dutch dairy sector: dilemmas for sustainability

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ABSTRACT

Since the European Energy Efficiency Directive, a lot of attention has been paid to energy saving measures, including how to overcome the barriers for implementation. This paper addresses the dilemmas of the Dutch dairy sector, where farms are getting bigger and mechanization is increasing, while at the same time the sector is aiming for improved energy efficiency and sustainability. With an online tool which systematically recorded the energy performance of dairy farmers, a unique dataset on farm energy use with more than 25,000 observations over the years 2015–2018 was obtained. This allows for a robust analysis of the determinants of energy efficiency in the sector, using panel data analyses. The results of this study reveal three major trends. First, the on-farm use of solar panels proves to be the most significant determinant for reducing non-renewable energy use. Second, gains in energy efficiency triggered by government policies are countervailed by the continuous trend of mechanization, with especially automatic milking systems causing lower energy efficiency. Third, the increasing economies of scale in milk production substantially improve per-unit energy efficiency. However, the increased need for mechanization related to higher on-farm production can cancel out this economies-of-scale effect. These findings add important new insights to the literature on cleaner production in farms and have important policy implications. Strategies for more energy-efficient farming should entail two directions for innovation: first, the stimulation of more energy efficient automatic milking systems, and second, the stimulation of solar energy production on farms including a better on-farm utilization of solar electricity.

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1. Introduction

The global per-capita consumption of livestock products has more than doubled over the past 40 years (FAO, 2009). As a result, the livestock sector has developed towards a major food producer, but also towards using an enormous amount of natural resources: on a global scale 30% of the ice-free land and 32% of freshwater is used for animal grazing and drinking. The livestock sector globally accounts to 40–50% of the agricultural Gross Domestic Product (FAO, 2009). Driven by population and income growth as well as urbanization, a substantial growth of the consumption of meat and milk for the coming 20 years is projected (Herrero et al., 2016). The dairy sector traditionally responds to this growing demand with intensification, which is revealed in an increase in the stocking rate

of cows, milk production per cow and cows per hectare (Alvarez et al., 2008).

Several authors describe the positive relationship between company size and energy efficiency in various industrial sectors. However, at the same time it was revealed that production growth is the dominant contributor to the increase of greenhouse gas (GHG) emissions (Kim and Kim, 2012), while changes in the energy mix, especially the contribution of renewable energy sources, reduce the GHG emissions (Marques et al., 2019). Therefore, the European Energy Efficiency Directive, including the 2018-amendment, sets targets for energy efficiency as well as for the reduction of fossil energy use on a national level, in order to decrease GHG emissions. Recently, more sustainable ways of growth in industry and agriculture are reported, such as intensification based on the circular economy model (Xue et al., 2019; Esposito et al., 2020). Common features in these recent agricultural models are sustainable feed supply on the input side, responsible

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manure treatment on the output side, energy efficiency and the use of renewable energy sources as key strategies to reduce fossil energy use. Therefore, increasing the energy efficiency as well as replacing fossil energy by renewables such as solar, wind or biomass, are of paramount importance for sustainability on farms.

Many studies have addressed the energy efficiency of milk harvesting (Seefedpari et al., 2020; Shine et al., 2018; Upton et al., 2014), while an increasing number of studies are focussing on the role of renewable energy on dairy farms (Steidle Neto and Carvalho Lopes, 2020; Nacer et al., 2016; Houston et al., 2014). Despite this growing body of research, it remains difficult to identify where and how meaningful improvements in energy efficiency have been made in the last decades. For industry as well for agriculture, reported differences in energy efficiency seem to depend more on definitions and methodological differences in the measurement of energy use, rather than on differences in actual management or technologies used (Abeelen et al., 2019; Ahokas et al., 2014). Two major issues are described in the recent literature that highlight the dilemmas of making dairy farms more sustainable. The first challenge is how to capture synergies between decreasing the use of fossil fuels and increasing productivity (Wang et al., 2016), while the second challenge is about reducing fossil fuel use under increasing mechanization (Jiang et al., 2020). The aim of this paper is to contribute to a better understanding of these two challenges.

More specifically, the paper aims to reveal the most important determinants of energy efficiency of dairy farms in the Netherlands, using a large dataset of more than 25,000 farmer records over the years 2015–2018. Because of its relevance for climate policy, our main focus is on energy efficiency of non-renewable energy use, although we also research the effects for total energy use. This dataset goes back to the 'Sustainable Dairy Chain' in 2009, which is one of the few schemes in Europe systematically documenting different types of energy efficiency projects for more than ten years. This initiative was a response to a covenant, which has been in force in the Netherlands since 2008, aiming to accelerate the implementation of techniques for energy conservation and use of renewable energy on farms, as well as to reduce GHG emissions (Rijksoverheid, 2008).

Given the large dataset of 25,000 farmer records over the years 2015–2018 and the large number of potential determinants of energy efficiency considered in the analysis, this paper is unique in the current literature. Other than previous studies which are solely based on cross sectional data, this study provides a panel dataset allowing for a more accurate and meaningful assessment of energy efficiency in the Dutch dairy sector. The structure of the paper is as follows. Section 2 addresses the characteristics of Dutch dairy farms, followed by a comprehensive literature review and the hypotheses. Section 3 describes the methods, the data collection and the dataset. Section 4 presents the results, which are discussed in Section 5. Section 6 concludes.

2. Background

2.1. Scope of the study

The Netherlands is known worldwide as a dairy country, with the typical pasture landscape with grazing cows. The proximity of Rotterdam harbour allows for easy imports of feed and exports of dairy products. The number of dairy farms in the Netherlands decreased from 29,400 in 2000 to 17,900 in 2016, while the average size of farms increased from 57 to 98 cows in the same period. A policy change that heavily affected the Dutch dairy industry was the abolition of the EU milk quota system in 2015 for individual farms, which was accompanied by a new Dutch manure policy to limit the phosphate excretion via manure on expanding dairy

farms. As will be demonstrated later in the article (see Section 3.3), this policy change significantly influenced the characteristics of 'an average Dutch dairy farm'.

The average Dutch dairy farm in 2016 maintained a herd of 87 cows, of which the majority are Holstein Friesian cows. The average size of the farmland is 50 ha of which 80% is grassland and 20% is used for the production of maize. The annual average milk production per farm is 707 ton milk per year, which implies an average milk production per cow of 8160 kg milk year (Klootwijk et al., 2016). A schematic overview of the typical milk production system in the Netherlands is presented in Fig. 1, which explicitly highlights the system boundaries of this study indicated by the orange elements (with the blue elements being excluded from the analysis). This paper analyses the determinants of energy efficiency in the core business of dairy farms: milk production. Electric energy is used for a wide range of processes, which are addressed below.

For the purpose of this paper we use the simple per-unit energy efficiency definition (unless mentioned otherwise): Energy efficiency = Energy per unit of output (Marques et al., 2019). As reducing GHG emissions is one of the most important global environmental targets, we only use the fossil energy input (kWh) for Energy, in which renewables are excluded. For output we take kg milk.

2.2. Literature review on energy efficiency in dairy farms

In the recent general literature concerning industrial energy efficiency, the authors did not yet reach a consensus on which methods should be applied, nor which variables should be taken into account for which analyses (Marques et al., 2019; Abeelen et al., 2019). Such methodological issues include differences in system boundaries, scopes and definitions varying between studies, as well as differences in the number of companies and variables considered in the study (Ahokas et al., 2014). The positive effects of energy saving measures are undisputed, the main drivers are economical, while the main barriers often are organizational (Lawrence et al., 2019; Abeelen et al., 2019). The positive effect of renewable energy is emphasized for reducing GHG emissions, but for energy efficiency also rebound effects are reported (Marques et al., 2019; Qui et al., 2019). There is a broad consensus of production volume promoting energy efficiency (Wang et al., 2017), but it is also noted that in a broader perspective larger companies will have higher GHG emissions and that small scale companies should be advocated from that point of view (Pan et al., 2019; Wang et al., 2016). Mechanization will usually decrease energy efficiency, and from a broader perspective GHG emissions will be increased (Jiang et al., 2020; Aguilera et al., 2019).

Also for dairy farms there is ample literature on the determinants of energy efficiency, offering a variety of insights. To accurately study energy efficiency of dairy farms, research needs to consider that the structure of dairy farms varies widely in terms of size of herd, type of milk- and cooling systems, type of manure disposal systems, grazing or non-grazing systems, presence of additional devices, and the extent to which farmers use own machinery or involve contractors. Also, the used energy mix differs between dairy farms (Seefedpari et al., 2020; Steidle Neto and Carvalho Lopes, 2020). A short summary of the most recent or most relevant energy performance in the literature of the different processes depicted in the "electricity demand" box of Fig. 1, is provided in the following.

Several papers distinguish **conventional milking systems (CM)** and **automatic milking systems (AMS)**, which are major energy users on a dairy farm. In the literature, energy uses for milking systems are found ranging from 4.4 to 17.0 Wh/kg milk for CM and 18.0 to 39.3 for AMS (Upton et al., 2013; Shine et al., 2018; Murgia

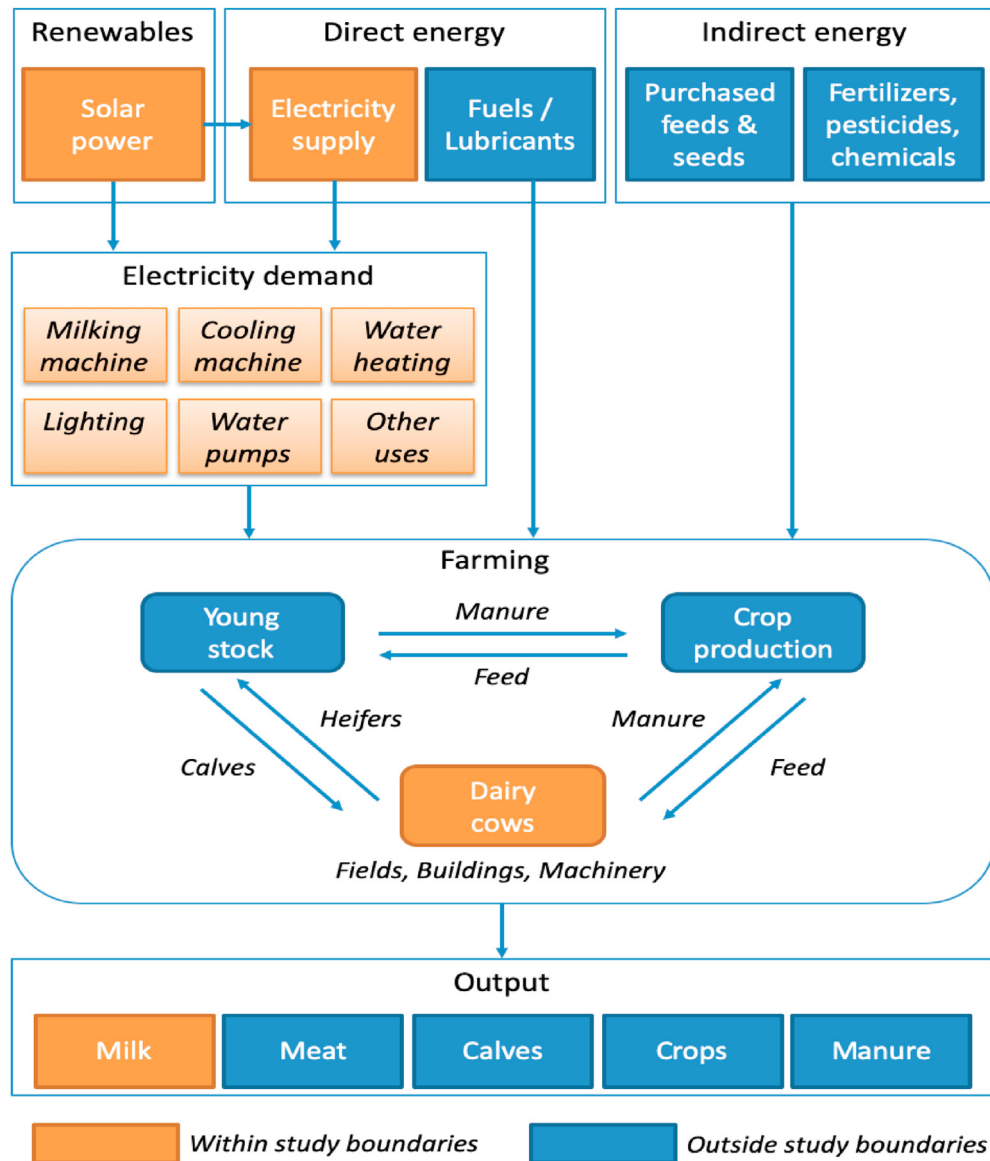


Fig. 1. Energy use on a typical Dutch dairy farm (based on Ahokas et al., 2014; Upjohn et al., 2014).

et al., 2013; Pezzuolo et al., 2020). To maintain high milk quality, including low bacteria counts, **milk cooling** ensures a raw milk temperature of around 3–4 °C. Also cooling systems are major energy users. Data are reported from 6.4 to 33.4 Wh/kg milk for CM and 6.4 to 38.7 Wh/kg milk for AMS (Upton et al., 2013; Upton et al., 2014; Shine et al., 2018; Houston et al., 2014). Warm water is required for technologic needs, such as cleaning milking equipment, materials and buildings. The main systems for **water heating** are electric boilers or boilers heated by natural gas. Data range from 3.3 to 22.8 Wh/kg milk for electric boilers (Upton et al., 2014; Shine et al., 2018; Rajaniemi et al., 2017). Appropriate **lighting** can improve productivity and safety on a dairy farm. Average values for the contribution of lighting on the total milk harvesting process was 1.4 Wh/kg milk (Shine et al., 2018) to 32.1 Wh/kg milk for incandescent lamps (Houston et al., 2014). Besides the unit operations as mentioned above, usually a number of **other electricity uses** are common in dairy farms, such as well water pumps, ventilation systems, cow brushes, automatic manure scrapers, automatic feeding systems and drinking automats for calves. Data for miscellaneous energy users range from 4.1 to 38.8 Wh/kg milk

(Upton et al., 2013; Murgia et al., 2013; Neto et al., 2020).

Table 1 summarizes for the different process steps the minimum and maximum values for energy use found in the literature, revealing a range between 20.1 and 168.9 Wh/kg milk for CM and between 33.7 and 196.5 Wh/kg milk for AMS.

2.3. Hypotheses

Based on the insights from the presented general literature review and additional studies, four testable hypotheses are formulated for the empirical analysis of the determinants of energy efficiency of dairy farms in the Netherlands. Generally, it can be assumed that the consumption of energy is related to the production volume, the structure of production activities, and the implementation of efficient technologies. Besides, it is influenced by energy saving policies designed by governments since the early 1970s. Initially, the latter were mainly a reaction to the oil crisis and the resulting steep rise in energy prices, but in the 1990s climate change became an increasingly dominant motivation for energy saving policies (Aguilera et al., 2019). Therefore, the first hypothesis

Table 1
Data on electricity use of different processes in dairy farming, compiled from existing literature.

Process step	Minimum value Wh/kg milk		Maximum value Wh/kg milk		Most relevant references
	CM	AMS	CM	AMS	
Milking machine	4.4	18.0	17.0	39.3	Ahokas et al. (2014), Rajaniemi (2017), Upton (2013), Murgia (2008; 2013), Shine (2018), Houston et al. (2014), Pezzuolo (2020), Steidle Neto and Carvalho Lopes (2020), Calcante (2016).
Cooling machine	6.4	6.4	33.4	38.7	Pezzuolo (2020), Steidle Neto and Carvalho Lopes (2020), Shine (2018), Ahokas et al. (2014), Rajaniemi (2017), Upton (2013), Murgia (2008), Shine (2018), Houston et al. (2014).
Water heating	3.3	3.3	22.8	22.8	Steidle Neto and Carvalho Lopes (2020), Upton (2013), Rajaniemi (2017), Shine (2018), Murgia (2013), Houston et al. (2014), Upton (2014).
Lighting	0.7	0.7	32.1	32.1	Steidle Neto and Carvalho Lopes, 2020, Murgia (2008), Shine (2018) Houston (2014), Upton (2013), Upton (2014).
(Well) Water pumps	1.2	1.2	24.8	24.8	Shine (2018); Houston et al. (2014), Steidle Neto and Carvalho Lopes (2020), Murgia (2013), Upton (2013).
Miscellaneous	4.1	4.1	38.8	38.8	Ahokas et al. (2014), Upton (2013), Murgia (2013), Steidle Neto and Carvalho Lopes (2020), Houston et al. (2014).
Total farm electricity use, added processes	>20.1	>33.7	< 168.9	< 196.5	

(H1) refers to the importance of energy saving measures in response to energy policies.

H1. Energy saving measures are the most important driver for increased energy efficiency in the Dutch dairy sector.

With respect to the effect of the production volume of milk on energy efficiency, different studies report different effects (Lockeretz, 2012; Shine et al., 2018). In the chemical industry, a higher production level improves the utilization rate of machinery and is associated with higher levels of energy efficiency (Wang et al., 2017). Accordingly, we formulate a second hypothesis (H2).

H2. Energy efficiency increases with increased production volumes of milk.

Despite energy saving efforts, the continuing trend of mechanization in the dairy sector poses the threat of a decline in energy efficiency. It is generally recognized that the energy use of an automatic milking system (AMS) is significantly higher than the energy use of conventional milking systems (CM, Calcante et al., 2016). Therefore, the third hypothesis (H3) focusses on the introduction of AMS.

H3. Mechanization of milking systems (AMS) is an important driver for decreased energy efficiency in the Dutch dairy sector.

The fourth hypothesis addresses the role of solar panels on dairy farms. While solar panels are not an energy saving measure, they do reduce the use of fossil fuels on the farm. Farmers using solar panels have been found to be generally more environmentally conscious. Therefore, these farmers might be more inclined to also take energy-efficiency measures on their farms (Beckman and Xiarchos, 2013). The fourth hypothesis (H4) focusses on this relationship between the presence of solar panels and overall energy efficiency of a farm.

H4. Dairy farms using solar panels are more energy efficient.

3. Material and methods

3.1. Data collection

In 2012, an online survey tool for electricity use on farms was developed by the Dutch Dairy Association (NZO). In the online tool, detailed information was gathered of milk production, the use of electricity and the own production of energy. In addition, detailed information of the farm architecture was collected, such as the type of milking system, cooling system, water heating system and other processes. Also, information on the various options for energy

saving, such as precoolers and heat exchange, was assembled. The online tool was launched in 2012 as a voluntary benchmarking instrument. As long as there are no changes in company structure, the dairy farmers only have to fill in their dairy production and energy use. In case of a changed company structure, such as the placement of a precooler, only the respective aspect has to be adapted. In return, the dairy farmer can observe his or her own energy use, and compare these results to the energy performance of other companies. Because active participation before 2015 was limited, this study uses data for the period 2015 to 2018 to analyse the determinants of energy efficiency in the dairy sector.

3.2. Data analyses

To test our hypotheses, a series of random-effects panel regression analyses was performed (Greene, 2012; Long, 1997). Several model specifications have been tested. The Breusch-Pagan test supported the random-effects model over the pooled model and the Hausmann test supported the fixed-effects approach. As this study is interested in both longitudinal and cross-sectional relationships, we still applied a random-effects model, as the fixed-effects model only assesses longitudinal effects. For the purpose of verification, we also conducted fixed-effects models, and the results are in line with the findings from the random-effect models.

Data is obtained for individual farms over time, as well as between farms cross-sectionally for the period 2015–2018, making it with more than 25,000 observations the most comprehensive dataset of electricity use by dairy farmers in the literature so far. The analysis is restricted to electricity consumption as other fuels are hardly used in Dutch dairy farms, except for the occasional use of natural gas or propane in boilers. Indirect energy use from e.g. feed and fertilisers are excluded from this study, as well as the direct use of diesel in tractors for crop production. The net electricity input from solar panels is recorded, but other types of renewable energy generation, such as windmills and manure digesters, are excluded. The electricity production of windmills and digesters often is supplied directly to the grid, while peripheral equipment is raising the on-farm energy use, distorting the actual energy use of milk harvesting. Other business activities, such as a farm-shop or recreation facilities, are also excluded from this analysis as these activities cause differences in energy use that are independent of milk production. Electricity used in the farm-household is excluded for the same reason. Based on experiences of the Dutch Dairy Association, data points smaller than 20 Wh/kg milk or larger than

150 Wh/kg milk are considered to be based on inadequate basic information and are therefore removed from the database (i.e. 4.1% of the data). The analysis was conducted using the statistical software Stata 16. The dependent variable in the regression model is on-farm electricity use, expressed in *Wh/kg milk*. A complete overview of the descriptive statistics of the variables is provided in Table 2.

3.3. Data description

The implementation of the most important energy saving measures over time in the observed farm sample is consistent but slow. Also the percentage of solar energy in the final end-use increased from 6.0% in 2015 to 7.3% in 2018 and the average percentage of solar energy which is returned to the grid is 54.0%, reflecting a large potential for better on-farm use of solar energy. The type of milking parlour is discussed frequently, distinguishing between AMS and CM. Table 2 shows that with a share of 64%, conventional milking parlours are the dominant system. Other CM systems, such as the rotary milking parlour, the tie-stall and the swing-over have minor shares varying between 3 and 6%. Some companies have multiple types of systems. The share of AMS in Dutch dairy farms increased from 22.4% in 2015 to 24.9% in 2018. As depicted in Fig. 2, each type of milking system has a specific range of production volumes. For example, on average a rotary milking parlour produces five times more milk than a tie-stall.

Our results show a continuous growth in average production

volume of farms, increasing from 820 tons of milk/year in 2015 to 930 tons of milk/year in 2018. Fig. 3 shows the development of the average production volume and the average energy efficiency of Dutch farms between 2015 and 2018. The average production volume increased considerably over this period. Related to the abolition of the milk quota system, in 2015 many dairy farmers enlarged their milking capacity. However, due to the new Dutch manure policy in 2015, many farmers could not yet enlarge their milking volume in 2015. This might be a possible explanation for the relatively poor energy efficiency in 2015.

4. Results

4.1. Determinants of energy efficiency

Table 3 shows the results of panel data regression analyses of the dataset both with random effects and with fixed effects models. We estimate both models for electricity use excluding solar energy ('non-renewable energy efficiency') and for electricity use including solar energy ('total energy efficiency'). The main model used in the analysis of the results is the random-effects model assessing non-renewable energy efficiency. This choice is motivated by the fact that, for climate policy and cleaner production, it is most relevant to look at reductions in GHG-emitting energy use, which means assessing the impacts on the use of fossil-fuel generated electricity excluding solar energy. However, for a more complete picture, results for overall energy use are also presented.

Table 2
Overview of the variables in the regression model.

Variable	Unit	Mean	Std. Dev	Min.	Max.	Type of variable
Dependent						
Electricity use	Wh/kg milk	51.84	18.89	20.01	149.76	Continuous variable
Independent						
Energy saving measures						
Precooler	Yes/No	0.58	0.49	0	1	Dummy variable (No = base category, Yes = 1)
Heat recovery	Yes/No	0.50	0.50	0	1	Dummy variable (No = base, yes = 1)
Extra efficient cooler type	Type of cooler	0.28	0.45	0	1	Dummy variable (Extra efficient cooler = base category, other cooler types = 1)
Energy efficient lighting	Installed light capacity (W)	2649	2487.7	50	49,200	Continuous variable
Time switches	Yes/No	0.43	0.49	0	1	Dummy variable (No = base, yes = 1)
Twilight switches	Yes/No	0.54	0.50	0	1	Dummy variable (No = base, yes = 1)
Farm architecture						
Production	Ton milk/year	898,246	536,997	23,573	7,960,327	Continuous variable
Main milking system	Type of main milking system					Dummy variable. Milking parlour = base category, other system = 1)
Milking parlour		0.64	0.48	0	1	Dummy variable (Yes = base, no = 1)
Automatic milking system		0.24	0.43	0	1	Dummy variable (No = base, yes = 1)
Rotary parlour		0.06	0.23	0	1	Dummy variable (No = base, yes = 1)
Tie-stall		0.03	0.18	0	1	Dummy variable (No = base, yes = 1)
Swing over		0.03	0.17	0	1	Dummy variable (No = base, yes = 1)
Number of milking systems	Number	1.04	0.21	1	3	Discrete variable (1,2 or 3)
Solar panels	Yes/No	0.19	0.39	0	1	Dummy variable (No = base, yes = 1)
Electric boiler	Yes/No	0.56	0.50	0	1	Dummy variable (No = base, yes = 1)
Electric water pumps (irrigation)	Yes/No	0.12	0.32	0	1	Dummy variable (No = base, yes = 1)
Additional electrical devices	Number	0.23	0.65	0	5	Discrete variable (0,1,2,3,4, or 5)
Additional milk pumps	Yes/No	0.15	0.35	0	1	Dummy variable (No = base, yes = 1)
Additional vacuum pumps	Yes/No	0.53	0.50	0	1	Dummy variable (No = base, yes = 1)
Manure robot	Yes/No	0.32	0.47	0	1	Dummy variable (No = base, yes = 1)
Electric manure mixers	Yes/No	0.08	0.28	0	1	Dummy variable (No = base, yes = 1)
Feed robot	Yes/No	0.02	0.13	0	1	Dummy variable (No = base, yes = 1)
Defrost of well water	Yes/No	0.63	0.48	0	1	Dummy variable (No = base, yes = 1)
Cow brushes	Number	1.03	1.01	0	4	Discrete variable (0,1,2,3 or 4)
Other variables						
Year 2015				0	1	Dummy variable (Yes = base, no = 1)
Year 2016				0	1	Dummy variable (No = base, yes = 1)
Year 2017				0	1	Dummy variable (No = base, yes = 1)
Year 2018				0	1	Dummy variable (No = base, yes = 1)

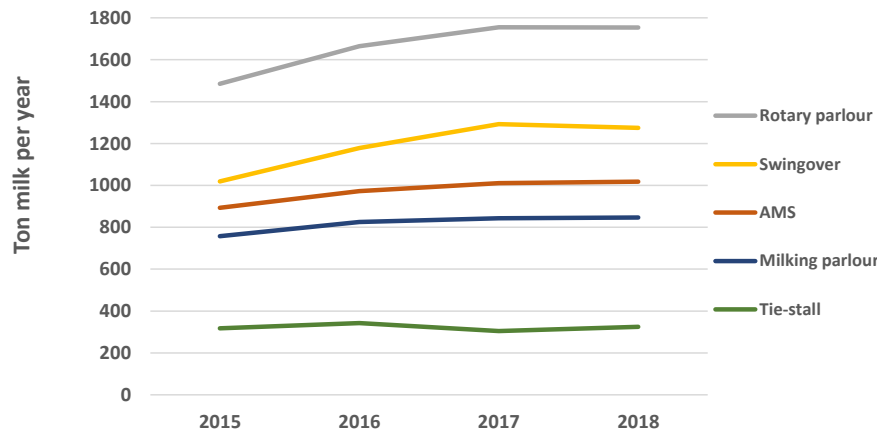


Fig. 2. Average milk production for different milking systems in the Netherlands 2015–2018.

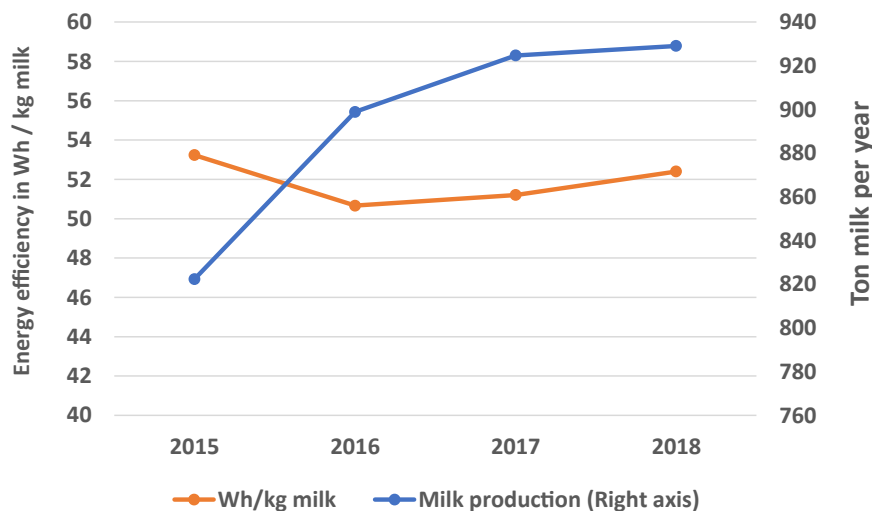


Fig. 3. Average energy efficiency and production volume (right axis) of Dutch dairy farms 2015–2018.

The choice for the random effects model as the main model, instead of the fixed effects model, is supported by the much higher explanatory power in terms of the R^2 value, and by the theoretical reasons described earlier (see Section 3.2). Nevertheless, the results are largely similar for both types of models. The time trend included in the random-effects models confirms the trend shown in Fig. 3, indicating that energy efficiency in the years 2016–2018 has significantly improved compared to 2015. The model-fit indicators suggest that the model explains the variation between farms better than variations within individual farms over the four years.

The results in Table 3 show that almost none of the energy saving measures have a significant impact on energy efficiency, unlike suggested in Hypothesis 1. The combination of AMS and precooler ($p < 0.05$) result in a significant improvement of energy efficiency, which is in line with findings in the literature (Rajaniemi et al., 2015). Furthermore, only twilight switches ($p < 0.01$) have a significant impact on energy efficiency. Also the presence of time switches ($p < 0.05$) is a significant determinant, however, contrary to our expectations, our analysis reveals a negative influence of time switches on energy efficiency. This counterintuitive result concerning the impact of time switches may have both behavioural and systemic causes (Brookes, 2000). Behavioural influences might

play a role, for instance as the standard settings of time switches may lead to more instead of less hours of lighting compared to manual operation. A systemic cause might be that time switches are mostly applied by 'mechanization-minded' farmers.

Our model suggests that an important factor contributing to an increased energy efficiency is a higher volume of milk production, which we set out to test in Hypothesis 2. This is an expected outcome, because more cows usually mean a more efficient use of machinery and buildings. The presence of an AMS is found to be an important factor negatively affecting energy efficiency, as suggested in Hypothesis 3. The most powerful measure to improve energy efficiency of fossil-fuel-generated electricity is to install solar panels. However, when we research total energy use including solar energy, contrary to our expectations formulated in Hypothesis 4, the total energy efficiency of farmers without solar panels is better. Other factors that significantly reduce energy efficiency include having multiple milking systems, additional milk pumps and other additional electric appliances. The presence of electric boilers and electric irrigation also seems to reduce energy efficiency, but as we did not account for the gas use of water heating systems, or the diesel use of electric irrigation, the energy efficiency effects of these systems need further examination.

Table 3

Results of the random- and fixed effects panel regression model, including data from 2015 to 2018.

Variable	Effects on Energy efficiency (Wh/kg milk)			
	Random Effects Model		Fixed Effects Model	
	Fossil energy only ('Main Model')	Solar energy included	Fossil energy only	Solar energy included
Farm architecture	Coëff. (std. error)	Coëff. (std. error)	Coëff. (std. error)	Coëff. (std. error)
Log. Production	−11.975 (0.313) ***	−13.375 (0.316) ***	−24.573 (1.538) ***	−28.184 (1.583) ***
AMS milking system	17.090 (0.721) ***	18.771 (0.728) ***	9.243 (1.544) ***	10.256 (1.589) ***
Rotary parlour system	4.343 (0.697) ***	4.6544 (0.698) ***	3.668 (1.957) *	4.497 (2.102) **
Swing over system	0.229 (0.790)	0.3101 (0.798)	−1.519 (2.004)	−1.882 (2.219)
Tie-stall system	−0.482 (0.707)	−0.8475 (0.715)	−0.235 (1.766)	−0.783 (1.568)
Solar panels	−15.456 (0.316) ***	1.3336 (0.321) ***	−11.843 (0.795) ***	3.653 (0.785) ***
Nr of milking systems	1.689 (0.482) ***	1.8120 (0.494) ***	0.927 (0.657)	0.889 (0.683)
Electric boiler	6.298 (0.267) ***	6.9860 (0.270) ***	1.420 (0.618) ***	1.788 (0.606) ***
Electric water pumps (irrigation)	6.373 (0.460) ***	7.1579 (0.461) ***	2.150 (1.317)	2.448 (1.465) *
Nr of additional devices	1.440 (0.198) ***	1.3554 (0.201) ***	1.132 (0.361) ***	0.872 (0.368) **
Additional milk pumps	1.143 (0.289) ***	0.8599 (0.297) ***	1.071 (0.437) **	0.756 (0.437) *
Add. vacuum pumps	−0.006 (0.238)	−0.1558 (0.244)	−0.27 (0.338)	−0.092 (0.338)
Manure robot	−0.144 (0.136)	−0.3045 (0.142) **	−0.069 (0.138)	−0.244 (0.145) *
Manure mixers	0.025 (0.213)	0.1877 (0.221)	0.076 (0.215)	0.225 (0.222)
Feed robot	0.719 (0.455)	0.4808 (0.472)	0.686 (0.453)	0.439 (0.480)
Defrost of well water	−0.178 (0.134)	−0.0415 (0.140)	−0.075 (0.133)	0.077 (0.140)
Cow brushes	−0.037 (0.066)	−0.0768 (0.068)	−0.045 (0.068)	−0.089 (0.071)
Energy saving measures				
Precooler	0.191 (0.348)	0.4898 (0.352)	−0.022 (0.662)	−0.048 (0.677)
AMS + precooler	−1.284 (0.702) **	−1.6530 (0.710) **	1.504 (1.457)	1.350 (1.490)
Heat recovery	0.444 (0.341)	0.5595 (0.344)	−0.148 (0.751)	−0.037 (0.765)
AMS + heat recovery	−0.221 (0.615)	−0.3201 (0.623)	−0.639 (1.337)	−1.324 (1.488)
Extra efficient cooler	0.071 (0.312)	0.1656 (0.315)	−0.061 (0.646)	0.195 (0.623)
Log. Efficient lighting	0.061 (0.077)	−0.0093 (0.080)	0.0064 (0.078)	0.010 (0.083)
Time switches	0.349 (0.141)**	0.3441 (0.147) **	0.310 (0.141) **	0.319 (0.148) **
Twilight switches	−0.403 (0.134) ***	−0.2275 (0.139)	−0.455 (0.131) ***	−0.303 (0.138) **
Year				
Year 2016	−1.927 (0.156) ***	−1.9336 (0.162) ***	−0.806 (0.197) ***	−0.570 (0.203) ***
Year 2017	−0.996 (0.157) ***	−1.2172 (0.163) ***	0.545 (0.225) **	0.679 (0.232) ***
Year 2018	−0.475 (0.159) ***	−0.4418 (0.165) ***	1.219 (0.244) ***	1.665 (0.249) ***
Constant	203.96 (4.171)***	222.66 (4.192)***	378.38 (20.709) ***	427.59 (21.303)***
Statistics				
Nr of observations	25,478	25,478	25,478	25,478
Nr of farmer-groups	8594	8594	8594	8594
R ² within	0.12	0.09	0.15	0.13
R ² between	0.40	0.36	0.19	0.16
R ² overall	0.37	0.33	0.18	0.14

Parameter estimates are shaded; *** = $p < 0.01$, ** = $p < 0.05$ and * = $p < 0.10$.

4.2. Predicted energy efficiency

To assess the quantitative impact of the variables of interest, the predicted energy efficiency is calculated for three 'representative' farm profiles, based on different levels of production volume, which we classified as small, medium and large. The corresponding production volumes, including all the other mean values for the variables as mentioned in Table 2 for these three groups, are presented in Table A in the Appendix. In order to calculate the predicted energy efficiency for these three scenarios, the values of the variables were chosen as follows. For continuous variables (i.e. production and lighting) we used the average value of the group, while for binary variables we used the dummy value '0' when the average value was smaller than 0.5, and the dummy value '1' when the average value was larger than 0.5. For categorical variables, we rounded off to the nearest integer. This simplifying simulation has certain drawbacks, because a variable with the value of 0.49 results in a dummy value of 0, while a value of 0.51 results in a dummy value of 1.

The results of this basic simulation, depicted in Table 4, show that a representative small farm has an energy use of 56.34 Wh/kg, a medium farm 49.26 Wh/kg and a large farm 42.64 Wh/kg. In other words, the result of 'intensification' from a medium (average) farm to a large farm yield energy efficiency gains of 6.62 Wh/kg

Table 4

Predicted energy efficiencies under different scenarios (calculations based on Main Model in Table 3).

Farm size	Wh/kg
Representative farms	
Small Farms	56.34
Medium farms	49.26
Large farms	42.64
Future scenarios	
Intensification and mechanization	58.22
Intensification, mechanization, and sustainability	43.19
Small-scale sustainable farming	41.94

milk (49.26–42.64). Yet, besides estimating the basic energy use, it is also important to assess the predicted energy use for alternative future scenarios. Three scenarios are envisioned. First, the "intensification and mechanization" scenario is simulated where current intensification and mechanization continues, without an explicit focus on sustainability. Uptake of AMS is already twice as large under large farms compared to small farms (32% versus 16%). This scenario entails representative large farms with an AMS, but without generating solar energy and without implementing extra energy efficiency measures. This scenario leads to a predicted energy use of 58.22 Wh/kg. In other words, mechanization

deteriorates energy efficiency with almost 16 Wh/kg milk (58.22–42.64).

Second, the “intensification, mechanization, and sustainability” scenario is simulated, where current intensification and mechanization continues while there is also a focus on sustainability. This scenario is characterized by representative large farms which have an AMS, but which do also produce solar energy and implement extra energy efficiency measures. This scenario leads to a predicted energy efficiency of 43.19 Wh/kg. In other words, sustainability measures for large mechanized farms yield energy efficiency gains of around 15 Wh/kg milk (58.22–43.19), which is almost fully caused by solar production.

Finally, the third “small-scale sustainable farming” scenario represents the call for more small-scale sustainable farming in the Netherlands. This scenario entails mainly small farms which because of their small size do not utilize an AMS and which produce solar energy while also implementing extra energy efficiency measures. This scenario entails a predicted energy efficiency of 41.94 Wh/kg, which provides the lowest score and which is much lower than 56.34 Wh/kg milk without solar production.

These results clearly show that an AMS can cancel out the efficiency gains of higher production, and that the production of solar energy is very promising in reducing the use of fossil fuel-generated electricity. Although the effects of energy efficiency measures were also included in this scenario analysis, they proved to have a negligible impact on energy efficiency.

5. Discussion

Based on the results described in the previous section, we examine the determinants of energy efficiency in relation to the four central hypotheses of this study.

5.1. Energy saving measures

Cost-effective energy saving measures, such as precoolers and heat recovery, are installed on more than 50% of the Dutch dairy farms, with progress being steady but slow. This is comparable with, for instance, the chemical industry, where it has been proven that economically viable technology is adopted at a slow pace (Abeelen et al., 2019). Nevertheless, the results of the regression model for energy saving measures do not fully meet our expectations regarding the energy efficiency gains achieved by the use of these technologies. No effect on energy efficiency was found for precoolers, heat recovery, extra efficient cooler types or efficient lighting, while in the literature ample evidence is found for energy saving effects of these measures for individual farms. Shine et al. (2018) found that with a plate heat exchanger for milk precooling, energy savings of 21% on cooling energy were achieved. Rajaniemi et al. (2017) reported savings of more than 25% on cooling energy for precooling systems. Only when tested specifically in combination with AMS, precoolers are evidently and significantly increasing energy efficiency ($p < 0.05$). All in all, we do not find support for hypothesis 1 (H1), stating that ‘energy saving measures are the most important driver for increased energy efficiency in the Dutch dairy sector’.

5.2. Production volume

The positive relationship between company size and energy efficiency is widely recognized in various industrial sectors (Marques et al., 2019; Kim and Kim, 2012). The literature shows mixed results regarding the impact of milk production volume on energy efficiency. Several authors recorded a negative relation between milk production and energy efficiency (Shine et al., 2018;

Upton et al., 2014). Other authors (Murgia et al., 2008; Neto et al., 2020) observed that higher milk production is associated with higher energy efficiency. These latter findings are in line with our observations. Table 3 shows that the production volume of milk is one of the strongest factors positively affecting energy efficiency of dairy farms. Therefore, the results of our regression analyses provide strong support for the second hypothesis (H2), stating that ‘energy efficiency increases with increased production volumes of milk’.

5.3. Mechanization

In industry, the need to increase labour productivity played a major role in mechanization processes. Also mechanization was responsible for a significant increase in GHG emissions (Aguilera et al., 2019). Shortall et al. (2016) compared AMS with CM and concluded that the installation of an AMS resulted in a 36% reduction of labour, but at the same time lead to lower cost-effectiveness and higher energy use, irrespective of farm size. Other authors also found that the presence of an AMS is associated with a decrease in energy efficiency (Rajaniemi et al., 2017; Murgia et al., 2008). Despite higher energy use and lower cost-effectiveness, the share of AMS is still increasing in the Netherlands. The share of automatic feed systems and manure robots is also increasing. This shows that the trade-off between an increase in energy use and reduced labour input is often solved in favour of the latter, which increases farmers’ freedom and flexibility (Calcante et al., 2016). Health arguments, the possibility of milking cows more than twice daily and the very high cost of labour in The Netherlands also increase the amenity of AMS. The results of the regression analyses shown in Table 3 indeed provide strong evidence that having an AMS is one of the most dominant factors for countervailing attempts to increase the energy efficiency of dairy farms in the Netherlands. Hence, we find strong support for the third hypothesis (H3) stating that ‘Mechanization of milking systems (AMS) is an important driver for decreased energy efficiency in the Dutch dairy sector’.

5.4. Renewable energy

Marques et al. (2019) described the contribution of renewable energy sources in improving energy efficiency in industrial sectors. Also many studies describe the positive effects of renewables on the reduced fossil fuel use of dairy farms (Neto et al., 2020; Houston et al., 2014; Beckman and Xiarchos, 2013). This paper illustrates that the presence of solar panels on a farm proves to be the most significant and robust determinant for improved energy efficiency. At the same time, when solar energy is included in the total electricity use, farms having solar panels are less energy efficient than farms without solar panels, which is contrary to our expectations. However, the availability of ‘free’ solar electricity makes it attractive for farmers to connect additional devices using electricity to prevent feed-in to the grid of the surplus electricity. Also, some carelessness can occur of this ‘free’ electricity consumption (Qui et al., 2019). Despite ample evidence in this study as well as in the literature for the positive effects of solar panels on reducing fossil energy use, we only found partial support for the fourth hypothesis (H4), stating that ‘Dairy farms using solar panels are more energy efficient’. However, as it is fossil-fuel generated energy use that is most pivotal for reducing greenhouse gas emissions, the generation of solar energy proves to be an important measure to make the sector more climate-proof.

5.5. Policy implications

In industry and agriculture, a lot of attention has been paid to a large number of energy saving measures, including how to overcome the barriers for implementation (Ahokas et al., 2014; Lawrence et al., 2019). Our analyses show that there are three dominant developments for energy efficiency: production volume, solar energy production and mechanization.

Farmers are facing the increasing challenge to keep their business competitive (Llanos et al., 2018). Higher milk production and labour efficiency are important drivers to choose for further mechanization. However, the use of AMS has a significant negative impact on energy efficiency. Given the results of our analyses, government policies focussing on the implementation of energy saving measures may not lead to more energy efficiency. Instead, stimulating the implementation of solar energy proved to lead to a significant reduction in non-renewable energy use. To further improve energy efficiency and to reduce the use of fossil fuels in the Dutch dairy sector, two innovations are pivotal. First, on-farm use of generated electricity from solar panels (electrification, batteries, hydrogen production) has to be further promoted. Second, the energy efficiency of AMS has to be improved further through smart designs of machinery and cooling tanks (short distances), efficient vacuum pumps and air compressors, and ensuring proper maintenance to avoid leakages (Pezzuolo et al., 2020; Calcante et al., 2016).

6. Conclusions

This paper has presented an analysis of the main determinants of energy efficiency in the Dutch dairy sector. The unique dataset of more than 25,000 farm-records over the years 2015–2018 and the comprehensive set of potential determinants allowed for a novel and rigorous assessment. Our main results are very specific and quantified, but comparable with previous conclusions in industrial sectors. The broad range of determinants of energy efficiency found in our study indicate a great potential for improvements of farm processes.

The results of this study clearly show that the most important factor for enhancing energy efficiency of non-renewable energy use is the on-farm implementation of solar panels. Higher production also strongly increases energy efficiency. Nevertheless, the need for AMS will increase with higher production levels, which has a large negative influence on non-renewable energy efficiency. It is important to mention that in this study energy efficiency is calculated per unit of production, while for combatting climate change it is total energy use that matters. While production increases per unit energy efficiency (if not cancelled out by mechanization), total farm energy use and related greenhouse gas emissions still increase with higher production. This is extra relevant given the EU Energy Efficiency Directive, which demands reductions in fossil fuel use in addition to improved energy efficiency. Despite well-described energy saving effects of measures such as precoolers and heat exchange, these effects are overruled by several other factors of farm design. Besides the impact of solar production, the production volume and AMS, the utilization of additional milking systems and additional other electric devices also has a significant influence on energy efficiency.

The results of this study imply a vast challenge for governments, in cooperation with machine designers and constructors, to stimulate and develop more cost-effective and energy efficient AMS. In addition, on-farm production of solar energy should be further promoted and incentivised. Nonetheless, it is important to note that with energy efficiency the findings of this study concern just one facet of cleaner production in dairy farms; we do not assess the

impact of production volume, mechanization, and the other evaluated factors on nitrogen emissions, biodiversity and animal welfare, which are all essential in making the sector more sustainable.

CRedit authorship contribution statement

Albert Moerkerken: Conceptualization, Writing - original draft, Writing - review & editing. **Sem Duijndam:** Writing - review & editing, Formal analysis, Methodology, Software, Conceptualization. **Julia Blasch:** Writing - review & editing, Validation, Methodology. **Pieter van Beukering:** Writing - review & editing, Visualization, Supervision. **Arnoud Smit:** Data collection, Writing - review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2021.126095>.

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