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Evaluating integrated impacts of low-emission transitions in the livestock sector

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ABSTRACT

This paper provides the results of a combined qualitative and quantitative assessment of key impacts for two low-emission transition pathways for the Dutch livestock sector. These impacts or side-effects can be positive or negative. Both pathways were designed to meet a sector specific methane emission reduction target of 33 % in 2030 (relative to 2005). The qualitative assessment with stakeholders resulted in developing off-model quantifications to better reflect expected changes in system dynamics and development of more realistic transition pathways used for macro-econometric (E3ME) and atmospheric (TM5-FASST) modelling.

We found that each low-emission transition pathway has a unique footprint of positive and negative impacts. This footprint is largely shaped by the combination of existing and new technologies, infrastructure used, and practices deployed. We consider the analysis and results relevant for climate policy and governance processes where there is a need to develop transition pathways that are optimised to meet different sustainable development goals.

1. Introduction

The use of integrated assessment, agent-based, and environmental models for climate and energy policy analysis (Grubb, 1993; Francis and Strachan, 2017) is becoming more relevant as there are a multitude of dynamic factors relevant for enabling transitions (Francis and Strachan, 2017; Holtz, 2015). A better insight into societal, technological, and economic systems as well as behavioural dynamics is relevant for governing transitions (Loorbach et al., 2008) within the energy, and other sectors like agriculture. With renewable energy set to take on a larger share of the future energy mix, the spatial implications of wind, solar and biomass become more relevant. Particularly, in relation to possible competing uses of land for agriculture and forestry (e.g. food, animal feed, fibre). As a result, there is a need for a better qualitative and quantitative understanding of the spatial impacts of land use change (Hasegawa, 2017) and the scope and magnitude of potential co-benefits and adverse side-effects from climate actions in science and policy making. (IPCC, 2014) recognises that, *"despite the growing attention in policymaking and the scientific literature since AR4, the analytical and empirical underpinnings for understanding many of the interactive [side-]effects are under-developed."*

We focus on integrating insights from stakeholders with a macro-econometric and an environmental (air quality) impact assessment model (resp. E3ME and TM5-FASST) to quantify the scope and magnitude of a number of side-effects/impacts associated

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with two low-emission transition pathways for the livestock sector in the Netherlands. The first pathway constitutes a substantial reduction of the domestic cattle herd and the second pathway combines integrated manure management with a more moderate reduction of the cattle herd. Within the economic modelling with E3ME we introduce three land use scenarios as grassland could become available resulting in a reduction of cattle herds. These scenarios are: i) no land use change, ii) grassland conversion into food crops, and iii) conversion into flower crops and forest area. While stakeholders indicated that the displacement of dairy cattle farming could occur and would have significant environmental and social risks for the target countries, we were not able to simulate any intra-EU displacement scenarios for the macro-econometric impact assessment with E3ME within the scope of this paper.[2]

However, we had access to the TM5-FASST atmospheric model[3], which enabled us to simulate and quantify the impacts on air quality and human health as a result of the displacement of dairy farming activities to other EU regions.

For the integrated impact assessment we used a risk and opportunity based approach to explore with stakeholders which positive and negative impacts they expect could occur if and when the selected transition pathway is implemented at the sector level. The assumption of sector-wide scaling is relevant to explore consequential risks and opportunities at the market system level. Consequential risks include all unintended negative side-effects of a transition pathway at the sectoral or national level. At the same time there can also be unintended positive outcomes or opportunities resulting from a transition. The analysis of all possible consequential risks and opportunities goes beyond the development of an individual project, and is more about the impacts or consequences of a sector/country wide transformation (i.e. transition) at the system level. See editorial to the Special Issue by Lieu et al. (forthcoming) in this series for a more detailed discussion on consequential risks and opportunities.

To support the E3ME and TM5-FASST modelling, some off model quantifications were used to better define our transition pathway design, associated investment, and implementation trajectories. The off model quantifications are a direct result of the insights gained through stakeholder consultations. This allowed us to simulate more realistic transition trajectories (or narratives) in our modelling.

2. Pathway development and methodological approach

For the model simulations two transition pathways were developed (Table 1). The first pathway considers a reduction of the livestock sector (**RL**) and a reduction of the (dairy) cattle herd in particular. The second pathway focusses on a more moderate reduction of the cattle herd in combination with sector wide deployment of integrated manure management (**IMM**). IMM combines manure digestion and nutrient recycling technologies. These pathways were designed with the help of input from stakeholders and a basic analysis of a different livestock sector GHG mitigation options (included in Appendix B of the supplementary material).

In this paper, two models for quantifying specific impacts have been used. E3ME is a post-Keynesian energy-environment-economy macro-econometric model.[4] Economic growth in E3ME is demand-driven and supply-constrained, with no assumption of the economy being in full-employment equilibrium. It has empirically-validated dynamics (the time path of an economy). TM5-FASST (Van Dingenen, 2018) is a global source-receptor reduced model developed by the European Commission's Joint Research Centre that evaluates how air pollutants affect human health and agriculture systems. Using assumptions from meteorology and atmospheric chemistry, the model links emissions of pollutants in a given source region with downwind impacts.

One rationale for choosing a reduction of livestock as a specific mitigation solution are the 2017 election programs of several political parties. These included ambitions to reduce the size of the livestock sector in the Netherlands. More recently (in 2019) within the public debate on limiting nitrogen emissions in the Netherlands a 50% reduction of the livestock sector is promoted by some political parties. Also (Tirado, 2018) suggest that by 2050 the global production and consumption of meat and dairy should be halved. At the same time there are initiatives in the Netherlands livestock sector for increasing manure digestion and improving manure management both in (dairy) cattle[5] and pig farming. While these pathway rationales are valid within the country context, our analysis and discussion of side-effects remains a simplification, considering that realistic pathway designs include a broad mix of different low-emission technologies and practices, as well as a broader scope of analysis on side-effects. Knowing that our modelling time horizon is up to 2030, we acknowledge its limitations as there is also a need to explore the technological and socio-economic compatibility of our pathways with post-2030 policies where deeper cuts in GHG emissions are needed.

Both pathways were designed to meet a sector specific CH_4 reduction target of 33 % by 2030 (base year 2005). This target is derived from the initial proposal for a new EU Directive on Air Quality (EC, 2013) which listed national CH_4 emission targets for EU member states.[6] While currently, no such CH_4 specific targets are in place, it is clear that future low-emission strategies will also target CH_4 emissions in this sector. Already, the EU's Effort Sharing Regulation on binding national GHG emission reduction targets for the 2021-30 period indicates a reduction target of −36 % by 2030 (relative to 2005) for the Netherlands for all GHGs, including CH_4 (EC, 2018). A −33 % target implies that CH_4 emissions from agriculture in the Netherlands should be at 8.04 $MtCO_2$-eq in 2030. Relative to 2015 CH_4-emissions for agriculture[7] this translates into a 4.96 $MtCO_2$-eq. reduction effort for the 2015-30 period.

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[2] Within the scope of this project it was not possible in terms of resources and minimum data requirements to develop and simulate credible displacement transition scenarios for a range of other EU countries with E3ME.

[3] This case study was part of a larger project, TRANSrisk, where we had access to a range of models see http://transrisk-project.eu/virtual-library/transrisk-models

[4] www.E3ME.com

[5] See: https://www.jumpstartua.nl/ (in Dutch)

[6] Note: a specific national CH_4 emission target was not included in the final NEC Directive (EU 2016/2284).

[7] Please note that the all reported CH_4 emissions by agriculture stem from livestock.

Table 1
Two low emission transition pathways*.

Pathway	Reduction of livestock (RL)	Integrated manure management (IMM)
Target	-33% CH_4 emissions in 2030 relative to 2005; or 4.96 Mt CO_2-eq. reduction in 2030 relative to 2015 CH_4 emissions	
Main design elements	50 % reduction of domestic cattle herd in 2030 relative to 2015	23.6 % reduction of domestic cattle herd and processing of 100 % of all liquid cattle and pig manure captured in stable systems, or resp. about 39.67 and 13.41 mln. ton of manure
Key implication	Equivalent to a reduction of cattle herd with about ≈2 million animals	Equivalent to a reduction of cattle herd with about ≈1 million animals Building of ≈ 13,000 farm-scale IMM plants (cattle manure) and ≈ 70 industrial-scale IMM plants (pig manure)
Main cost elements	Cost for buying out cattle farmers	Costs for buying out cattle farmers and supporting investment in IMM plants

* More detailed information on pathway design can be found in Appendix A of supplementary material.

Within this paper not all identified side-effects have been quantified. The non-quantified side-effects (e.g. biodiversity, animal welfare, soil structure and soil fertility, diet-related human health) are versatile and often require specific models or cannot (yet) be quantified. For example, the impacts on a range of biodiversity indicators can provide a mixed picture and can sometimes be inconclusive. Reduction of the domestic cattle herd could involve marginalization of less productive and rarer cattle species to the extent that the remaining herd becomes too small to sustain a healthy gene pool. Furthermore, assuming grassland is converted into food crop land (FOOD scenario), this also has an impact on biodiversity as it affects the potential nesting area for meadow birds, as well as the availability and diversity of plants/flowers and insects. On the other hand, given that – on average – higher fertilization norms apply on grasslands, a conversion to food crop land might imply a lower level of nutrient run-off into surface water. This in turn could positively affect aquatic life in inland water bodies. In addition, there are not only domestic impacts to consider given the risk of displacement of cattle farming activities and associated impacts. Appendix C from the supplementary material provides more background information on the qualitative assessment of expected side-effects.

The quantification of side-effects for both pathways under three different land use change scenarios Table 1) was done via the global macro-econometric model E3ME. The TM5-FASST model was used for evaluation of air pollutant concentrations on human health in two different displacement scenarios (Table 3). Also, off-model quantifications were made to obtain quantitative impact results for specific side-effects. The following impacts were considered for quantification.

Off model quantifications

- Domestic land use change
- Production of renewable energy (biogas)
- Net domestic impact on greenhouse gas emissions, including sources of CH_4, CO_2, N_2O, and sinks (i.e. soil carbon changes)
- Domestic nutrient supply / demand balance from animal manure[8]

Macro-econometric assessment with E3ME

- Gross domestic product
- Agricultural output
- Domestic consumption
- Economy-wide price index
- Agriculture and economy-wide employment

Impacts of air quality on human health with TM5-FASST

- Net (global and regional) relative change in premature mortality (air quality related)

The off-model quantifications on domestic land-use change and a set of derived impacts have been used to enrich and expand the design and implementation trajectories of both pathways for the modelling with E3ME.

For the qualitative assessment of side-effects we used a conceptual framework (Spijker and Anger-Kraavi, 2018) to structure and evaluate the results of the stakeholder interviews. Key side-effects and changes in system dynamics associated with the pathways were identified via stakeholder interviews (Table 2).[9] The interviews all started with a brief explanation of the objectives of the livestock case study to explore barriers and negative outcomes of different transition pathways. Next, pathway design, alternative mitigation options, and the key expected side-effects were discussed.

In addition, the lead author took part in a series of stakeholder meetings hosted by the Dutch Ministries of Environment and

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[8] See Appendix G of the complementary material

[9] The pathway designs, findings, and conclusions presented do not necessarily reflect the views and opinions of individual stakeholders interviewed.

Table 2
List of stakeholder interviews.

Position	Organization	Details
Industry	Branch organization for renewable gas (Groen Gas Nederland)	Various dates; via telephone and e-mail exchanges
Industry	Energy Consultant, specialist in manure digestion	07-02-2017; semi-structured interview
Industry	Agriculture Association (LTO-Noord)	21-2-2017; semi-structured interview
Researcher	Wageningen Plant Research	02-03-2017; semi-structured interview
Policy maker	Ministry of Agriculture, Nature and Food Quality	19-04-2017; semi-structured interview and e-mail exchange
Researcher	Netherlands Environmental Assessment Agency	19-06-2017; semi-structured interview
Researcher	Wageningen University Research	14-08-2017; semi-structured interview
Policy maker	Ministry of Agriculture, Nature and Food Quality	17-11-2017; semi-structured interview
Researcher	Wageningen Environmental Research	Various dates; e-mail exchange

Table 3
Share of displacement of Dutch NH_3 emissions.

SE	Share	CEE	Share
France	+ 31.7 %	Poland	+ 24.65
Italy	+ 24.39 %	Czech Republic	+ 14.83
Spain	+ 24.39 %	Austria	+ 27.05
Greece	+ 19.52 %	Denmark	+ 33.47

Economic Affairs. These meetings provided input for a national climate action plan for the food and nature sectors (i.e. agriculture, horticulture, livestock, forestry). These sessions took part in the second half of 2017 and served as a good platform to identify key side-effects of different mitigation options.

2.1. Modelling scenarios

We deploy the E3ME model to analyse the macro-economic impacts of both pathways for three different land use change scenarios, namely003A

- NO LUC – No land use change will occur. This means that we do not model any alternative use of idle grassland that has a potential economic value,
- FOOD – All available grasslands – resulting from the respective reduction of cattle herd – will be converted for cultivation of food crops,
- FLOWER – All available grasslands will be partly converted to cultivate flower crops (with a high economic value) and partly for expanding the forest coverage (generally has a lower economic value). [10]

While we do not investigate the impacts of displacement of cattle farming to other countries with E3ME, we do explore the impacts of displacement with the help of TM5-FASST. Here we consider two scenarios for displacement of dairy farming. The first scenario assumes a displacement to Central and Eastern European countries (CEE), while the second scenario considers a displacement to Southern European countries (SE). We based these scenarios on dairy export data (ZuivelNL, 2016), and own assumptions regarding the reduced exports of Dutch dairy to EU countries (Table 3).

To quantify the human health effects related of displacement to other countries, we used TM5-FASST to assess the impact on the relative change of premature mortalities in 2020 and 2030 derived from the change in local NH_3 emissions. Ammonia emissions are an important precursor for the formation of particulate matter ($PM_{2.5}$) as it combines with other chemicals in air and forms secondary PM emissions. EU level emissions data from (EUROSTAT, 2017) and national emissions data for Dutch agriculture[11] (Bruggen, 2017) were used to calculate the net reduction of NH_3 emissions resulting from a respectively 50 % (RL) and 23.6 % (IMM) reduction in cattle farming in the Netherlands as part of the Benelux region (the TM5-FASST model does not disaggregate to the national level).

3. Results

3.1. Qualitative assessment

The stakeholder consultation provided information on the anticipated side-effects of both pathways. One of the major side-effects

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[10] For economic modelling the expansion of forest area is considered to have marginal economic impact in the 2018-30 period, as we do not assume planting of short rotation woody crops, but rather development of conventional forests with a primary nature conservation and recreational functions in addition to increased carbon sequestration

[11] See Appendix H of the supplementary material for more information on NH_3 emissions from agriculture

highlighted was the change in land-use. As a result of a reduction of the domestic cattle herd, a significant acreage of land for grazing and production of fodder would become available for alternative use. While the stakeholders had different preferences for alternative land uses, there was consensus about associated potential side-effects or market responses to specific changes in land use. The stakeholders also indicated that conversion of grassland could result in a release of soil carbon, and that more food crops cultivation would also increase the availability of food processing residues. Those additional residues would be suitable for use as animal feed or for biogas production.

Most stakeholders also indicated the risk of displacement of (dairy) cattle farming to other countries (i.e. carbon leakage). Also, the issue of animal welfare was considered an important side-effect in relation to the broader social acceptance of livestock farming. For the IMM pathway, for example, there could be an incentive to keep cattle indoors to capture more manure in stables for processing. For most of the identified human health, and local environmental side-effects (e.g. air pollution, soil compaction, soil acidification), there was general consensus about their relevance. Industry stakeholders identified the generation of renewable energy (i.e. biogas production) and production of organic fertilizers as having potential positive side-effects on animal and human health, mainly due to improved indoor stable air quality and reduced emissions from stables (due to improved sanitary conditions in stables).

Other relevant side-effects were identified via literature or news articles. For example, the Dutch sector initiative ‘the sustainable dairy value chain’ (in Dutch: ‘duurzame zuivelketen’), reports (Doornewaard, 2017) regularly on status and progress on a number of key development priorities, including climate neutral development, continuous improvement of animal health and animal welfare, retention of pasture grazing, and preservation of biodiversity and the environment.[12]

In the search for potentially relevant side-effects the authors also identified a potential adverse side-effect for animal welfare stemming from the Dutch phosphate reduction plan (EZ, 2017a,b) This plan included a subsidy for dairy farmers to terminate their dairy farming activities. The subsidy ensured that phosphate excretion from livestock would be brought down to agreed limits. However, the buy-out scheme attracted more dairy farmers with smaller herd sizes. Smaller dairy farms typically deploy higher levels of outdoor grazing, which is considered good for animal welfare. On top of this (Spijker, 2017), various Dutch media reported that – as a result of the phosphate reduction plan - the more rare cattle species would be at risk of reaching too low population levels to remain viable.[13]

3.2. Off model quantification of side-effects

3.2.1. Land use change

The qualitative assessment ensured that land-use change and related impacts were included in this paper. Given that the E3ME and TM5-FASST models do not focus on land-use change some off-model quantifications for land use change (and derived impacts) were made. For all off-model quantifications we focus on the impact for the year 2030 (i.e. we do not provide cumulative results for the 2018-30 period). For both pathways (RL and IMM) we estimate what acreage of land - currently used for producing roughage feeds (e.g. grass and fodder maize) - will be used for another purpose.

For the production of roughage feeds in 2016, 1,191,082 ha of agricultural land was used (CBS, 2018a,b). Of this 975,150 ha (or 82 %) comprised grasslands with the following composition:

- Permanent grassland – 691,216 ha
- Temporary grassland – 245,263 ha
- Nature grassland - 38,671 ha

The remaining 215,932 ha (18 %) is land used for fodder crops. Most roughage feeds are consumed by cattle, horses, sheep, and goats. Cattle represents the vast majority of grazing animals in the Netherlands for which roughage is produced. A 50 % reduction (RL) or 23.6 % reduction (IMM) in cattle livestock would imply that respectively a total of 595,541 ha or 281,095 ha agricultural land would be eligible for alternative use. In addition to considering that no land use change occurs (NO LUC), we developed two other scenarios for simulation purposes in modelling.[14]

3.3. FOOD scenario

Here we consider food crop production as alternative land use. We assume that acreage will expand proportionally to current (2016) land use shares for the main food crop categories (Table 4).

For each food crop, additional acreage (ha) of 118 % (RL) or 55.8 % (IMM) relative to 2016 levels is assumed. For the RL pathway this implies a more than doubling of the production of plant protein production suitable for human consumption by 2030.

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[12] Specific performance indicators include, GHG emissions of the dairy chain (in Mt CO_2-eq.), primary fuel consumption in the dairy chain (in m^3 natural gas equivalent per 1,000 kg milk), production of renewable energy (as % of consumption), proportion of farms below the threshold determined by the Foundation veterinary medicines authority (SDa), age at culling of dairy cattle, the reduction in use of antibiotics, the increase in outdoor grazing for cattle, proportion of dairy farms offering pasture grazing, proportion of sustainable soya, phosphate excretion of dairy cattle (in mln. Kg), ammonia emissions of dairy cattle (in mln. Kg).

[13] https://resource.wur.nl/en/show/Meet-the-Dutch-heritage-cattle-breeds.htm

[14] We do neither consider any legal or agronomical limits to the conversion of grassland for any alternative use, nor include any land use change in third countries resulting from reduced imports of animal feed (e.g. soy, maize).

Table 4
Land use conversion calculations (ha).

Agricultural food crop land	2016	% share (of total)	RL **595,541**	IMM **281,095**
Potatoes	157,900	0.31	186,705	88,124
agricultural crops	58,336	0.12	68,978	32,558
Grains	181,103	0.36	214,141	101,074
Grass seeds	9,974	0.02	11,794	5,567
Trade crops	12,297	0.02	14,541	6,863
Legumes	2,146	0.00	2,537	1,198
Sugar beets	70,722	0.14	83,624	39,470
Other agricultural crops	3,816	0.01	4,513	2,130
Set aside land	7,365	0.01	8,709	4,111
Total	503,660	1		

Table 5
Land use change impact for FLOWER scenario (ha).

	RL	IMM
Total ha freed up due to conversion of grassland for alternative use	595,541	281,095
Additional flower acreage	110,354	52,184
Additional forest area	485,187	228,911

3.4. FLOWER scenario

In this scenario (Table 5), the total acreage of land for alternative use will be allocated to both flower crop production (open soil), and for expanding forest area in the Netherlands. Current (2016) flower (open soil cultivation) acreage is at 93,520 ha. We assume that flower crop acreage will increase with the same proportions as within the FOOD scenario (i.e. + 118 % and +55.8 %) for both pathways. The remaining hectares are used for forest expansion.

From a purely economic perspective, allowing an expansion of high value flower cultivation could also economically offset the expansion of forest area that generally has a lower added value.[15] However, we acknowledge a range of potential issues that could limit the expansion of flower and/or forest area, such as the relatively high levels of pesticide use per hectare for key flower crops.[16],[17]

3.4.1. Biogas production

For the macro-econometric modelling (E3ME) we extended our initial pathway designs based on the insights from the changes in land use. Here we consider that an increase in cultivation of food crops (FOOD scenario) on the one hand would result in an excess availability of food processing residues, while at the other hand a reduction of the cattle herd would reduce demand for food processing residues for feed applications (e.g. wet feeds). For the FLOWER scenario only the 'reduced demand' for feed consumption applies. Appendix D of the supplementary material includes the background calculations for a) availability of food processing residues, as well as energy yield factors. Table 6 provides an overview of the net energy yields from biogas production from excess food processing residues. We focused only on the three main crop types, representing around 80 % of total current food crop acreage use.

As the production of biogas from food processing residues is directly linked to the RL and IMM pathways, we extended our pathway design for E3ME modelling by including an investment trajectory for biogas production from the anaerobic digestion of the estimated excess food processing residues.

3.5. Animal manure

While the anticipated increased production of biogas from food processing residues applies to both pathways, the IMM pathway also focusses on biogas production from animal manure. To quantify the energy yield from anaerobic digestion animal manure (pig and cattle) we applied a simplified approach. Results are shown in Table 7.

Under the FOOD scenario, the RL pathway would generate about 6.1 PJ renewable energy from food processing residues (see Table 6). Although significant, this is considerably lower relative to the IMM pathway, where a total of 15.4 PJ[18] of renewable energy

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[15] Estimations for potential non-economic gains of expanding forest area, like carbon sequestration, biodiversity gains, recreational purposes, etc. are not considered in this paper.

[16] To illustrate in 2016 almost 125 kg and 27.2 kg of pesticides per hectare of resp. lily and tulip (bulb) was used, while resp. 12.8. Kg and 3.9 kg was used for consumption potatoes and sugar beets.

[17] For economic modelling with E3ME we excluded the expansion of forest area. Although this is likely to have a positive economic impact in the 2018-30 period (i.e. we assume development of conventional forests which takes more time to become economically productive).

[18] 2.921 PJ from Tables 6,2.93 PJ and 9.57 from Table 7

Table 6
Net energy yields for FOOD scenario from use of excess food processing residues for biogas production in 2030 (in PJ).

		RL	IMM
Potatoes	Reduced demand	0.548	0.259
	Increased supply	1.294	0.612
	Subtotal potatoes	1.842	0.871
Grains	Reduced demand	0.491	0.232
	Increased supply	1.158	0.567
	Subtotal grains	1.649	0.799
Sugar beets	Reduced demand	0.788	0.372
	Increased supply	1.860	0.879
	Subtotal sugar beets	2.648	1.251
	Total reduced demand	1.827	0.863
	Total increased supply	4.312	2.058
	Grand total	**6.139**	**2.921**

Table 7
Renewable energy production from anaerobic digestion of animal manure in 2030*.

	Pig	Cattle
Manure availability in mln. ton (wet basis)	11.65	39.66
Biogas yield per ton of liquid pig manure (in m^3/ton manure)	25	30
Methane content (% CH_4/Nm^3 biogas)	56	56
1 m^3 CH_4 = MJ	35.9	35.9
Energy balance (correction factor for own energy use)	≈ 0.5	≈ 0.6
Total estimated net renewable energy output (in PJ)	**2.93**	**9.57**

* Energy yields from manure digestion only attribute to the IMM pathway.

would be produced. If we consider the FLOWER scenario, biogas production from food processing residues would be lower for both RL and IMM, down to respectively 1.83 and 13.35 PJ. This is because increased supply of food processing residues resulting from expansion of food cropping acreage does not occur. Here we also assume that expansion of flower and forest acreage will not result in large volumes of biomass to become available for bioenergy production up to 2030.[19]

3.5.1. Greenhouse gas emissions

The increased production of biogas also allows us to quantify the change in GHG emissions. For the FOOD scenario we can estimate the GHG savings resulting from the substitution of fossil energy.[20]

In addition to this we also provide estimates on CH_4 emission reduction, soil carbon changes from grassland conversion and changes in N_2O emissions. The results for the GHG calculations are shown in Table 8 for which the background calculations are presented in Appendix E of the supplementary material.

Specific off-model calculations for GHG emission reductions of the FLOWER scenario have not been made. For example, the uptake of CO_2 from the atmosphere by the planting of trees was not included in the assessment.[21] The results in Table 8 refer to the net domestic GHG impact for the year 2030, and do not consider displacement of these emissions (i.e. carbon leakage) to other countries.

3.6. Macroeconomic impacts

The agriculture sector (includes the livestock sector) contributes about 3.5 % of national output and includes a range of economic activities in the agro-food complex (e.g. food processing, primary production, distribution). The growth rate of the Dutch economy is about 1 % per year (Eurostat, 2018). The modelling with E3ME shows that the impacts on Dutch GDP depend on the scenario and what the meat and dairy cattle farming activities are replaced with. The RL pathway (NO LUC) can result in GDP loss of 0.6 % in 2030 while for IMM (NO LUC) the loss is 0.2 % relative to the baseline (Fig. 1 and Table 9).

Using all freed-up arable land (conversion of grassland) for growing protein crops (FOOD scenario) can somewhat compensate for this loss. Alternatively, when some of that land (see Table 5) is used for growing flowers (FLOWER scenario), that have high market value, the effect turns positive. At the EU-28 level small negative impacts on GDP can be felt in all scenarios but the FLOWER scenarios.

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[19] Residues from flower (bulb) cultivation are a) not typically available at centralised locations in large quantities, and b) are only suitable as co-substrate for digesters, not as primary feedstock.

[20] Economy wide changes in energy related CO_2-emissions in agriculture and other sectors are excluded from this estimate.

[21] Due to a lack of time and resources for (co-)developing specific reforestation strategies with stakeholders from the forestry sector.

Table 8
Net domestic GHG impact for RL and IMM pathways for the FOOD scenario in 2030 relative to 2015 (in $MtCO_2$-eq.).

GHG emission categories	RL	IMM	
CH_4 enteric	−3.8	−1.8	As per pathway design
CH_4 manure management	−1.15	−3.17	As per pathway design
Biogas – CO_2	−0.347	−0.875	From food processing residues and manure
Soil carbon	+1.43	+0.67	Release of soil C to atmosphere from conversion grassland to cropland
N_2O direct	−0.2	−0.095	Resulting from change in N supplied to soils
N_2O indirect	−0.019	−0.011	Resulting from change in N supplied to soils
Net domestic GHG impact	−4.086	−5.281	FOOD scenario, without carbon leakage

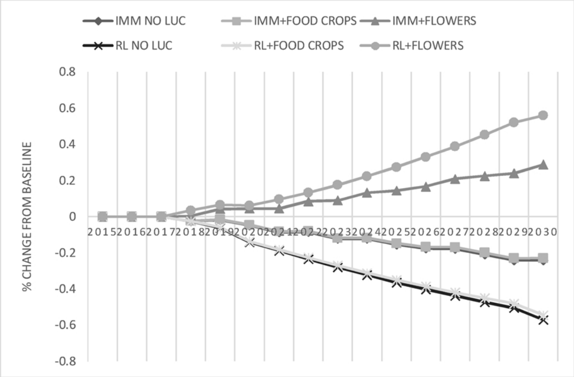

Fig. 1. Change in the Dutch GDP relative to baseline (in %).

Table 9
Change in macro-economic indicators in 2030 (% change relative to baseline).

	NL		EU-28	
GDP (real prices)	RL	IMM	RL	IMM
NO LUC	−0.571	−0.241	−0.035	−0.013
FOOD	−0.545	−0.229	−0.032	−0.012
FLOWER	0.559	0.288	0.061	0.032
Net Trade (as % of GDP)				
NO LUC	−3.393	−1.692		
FOOD	−3.250	−1.625		
FLOWER	2.864	1.259		
Agricultural output (real prices)				
NO LUC	−25.355	−11.360	−1.184	−0.512
FOOD	−24.270	−10.847	−1.121	−0.482
FLOWER	21.955	10.864	1.523	0.761
Economy wide employment				
NO LUC	−0.173	−0.073	−0.000	−0.000
FOOD	−0.165	−0.070	−0.000	−0.000
FLOWER	0.151	0.078	0.000	0.000
Agriculture employment				
NO LUC	−2.694	−1.217		
FOOD	−2.561	−1.160		
FLOWER	2.237	1.078		
Domestic consumption (real prices)				
NO LUC	−0.147	−0.141		
FOOD	−0.137	−0.136		
FLOWER	0.234	0.042		
Economy-wide price index (real prices)				
NO LUC	0.095	0.073		
FOOD	0.087	0.073		
FLOWER	−0.117	−0.029		

The main reason for observing only relatively small changes to the baseline results relates to the modest relative economic weight of the key affected sub-sectors (i.e. cattle farming and flower bulbs). The GDP of the Netherlands in 2015 was 683 bln. EUR (CBS, 2017a,b,c), the contribution of ground-bound livestock sector (that includes cattle), and open soil agriculture (includes flower bulbs) to GDP is resp. 8.5 and 3.3 bln. EUR (WUR, 2018) or resp. 1.25 % and 0.48 % of GDP. Knowing that our pathways predominantly affect primary production[22] of dairy and flower bulbs; which represent resp. 1.3 and 1.6 bln. EUR (WUR, 2018) or 0.19 % and 0.23 % of GDP in 2015, our results can be considered significant.

Looking at the aggregated price level of the overall Dutch economy there is likely to be a small increase in the price index for all non-FLOWER scenarios (up to 0.1 % in the RL NO LUC scenario in 2030). There will be also an initial small increase in the price level for the FLOWER scenarios related to the initial switch from growing more flowers and hence demand for investment products and time that is needed for the market adjustment to the increased flower production. This is followed by price drop (up to 0.1 % in the RL + FLOWERS scenario in 2030) caused by increased production of flowers.

Changes in the economy-wide price index will affect consumer behaviour in the Netherlands. In the RL pathway domestic consumption will be reduced by 0.15 % in 2030 (NO LUC). And in the RL pathway when economic value flower production increases by 118 % in 2030 compared to 2016 and domestic consumers react to falling flower prices by consuming more flowers there might be a 0.2 % increase in consumption. For IMM there is an increase of 55.8 % in terms of economic value in the production of flowers resulting in a 0.04 % increase in domestic consumption. However, this scenario does not take into account citizens' needs for compensation for less animal protein (less meat consumption due to higher meat prices) in their diets and assumes that consumption of flowers is purely price driven.

Similar trends are largely mimicked when we look at changes in the other selected macro-economic indicators for the Netherlands. For GDP and economy-wide (aggregated) employment we also provide impact data at the EU-28 level. We present the results for the year 2030 in Table 9.

The RL (NO LUC) scenario can result in losing 0.17 % (about 15 thousand) of jobs in Netherlands in 2030 out of which five thousand are directly employed in the agriculture sector. EU wide this would imply only a marginal overall loss (−0.000) of about 21,000 jobs[23] . Within the Netherlands there could arise a need to, retrain people and offer them alternative activities in the plant-protein based agro-food supply chain to mitigate this. However, this is assuming that no displacement of dairy farming to other EU countries will occur. Such intra-EU displacements could also fully or partially offset aggregate job loss. The FLOWER scenario has an increase in employment, while in the FOOD scenario the employment impact remains negative although at a minimally lower rate. First of all, this shows that decisions by market actors and policy makers on how to use scarce arable land can have important macro-economic implications. Secondly, the reduced aggregate employment losses for the FOOD and FLOWER scenario indicate that (partially) compensating employment opportunities in other sectors are likely with a change in land use.

The results show that the IMM pathway overall performs better relative to the RL pathway under the NO LUC and FOOD scenarios. For the FLOWER scenario the RL pathway generally has a higher impact (i.e. this is mainly due to more hectares of grassland converted for flower cultivation). While the impacts of both pathways have similar patterns, the results of the IMM pathway are less extreme (i.e. more moderate positive and negative side-effects). However, we have to note that the upfront investment costs and operational costs of the IMM transition pathway are considerably higher than the RL pathway. Where for the IMM pathway the investments and operational costs for installing and operating the IMM plants have to be made, there are no capital expenditures needed for RL as slaughtering or exporting cattle makes use of existing infrastructure. The cumulative costs (including CAPEX and OPEX) over the case study period (up to 2030) for the RL pathway add up to about 2.6 or 2.1 bln. EUR (for resp. the FOOD and FLOWER scenarios), these costs for the IMM pathway are much higher at 18.3 and 17.8 bln. EUR resp. (see Appendix F of the supplementary material for more background information). This larger up front financial requirement for IMM may become an implementation barrier at some point, but should be evaluated in the broader context of co-benefits and trade-offs. However, the longer the sector waits to start to implement the IMM pathway, the more likely it will be that the RL pathway will be implemented.[24]

3.7. Impact on air quality and on human health

The TM5-FASST model was used to assess the net impact of premature mortality resulting from an assumed displacement of dairy production to other regions in the EU (see Table 3). As cattle emit NH_3 emissions that contribute to atmospheric $PM_{2.5}$ levels, we expect that displacing cattle from densely populated regions to less populated regions results in a net reduction in premature mortalities. Table 10 shows that a displacement to Southern European countries would result in the highest net reduction of premature mortalities. The results show that not only the Benelux but also the ‘rest of the world’ benefits from displacement to Southern Europe. This mainly relates to the difference in population density in the Northwest European region (high population density) relative to that in Southern Europe (lower population density). Displacement of dairy production to Central Eastern European countries also results in a net reduction, but there would still be an estimated increase premature mortalities outside the Benelux region.

Please note that these displacement scenarios do not consider any regional differences in relative resource efficiencies for dairy production (e.g. NH_3 or GHG emission intensity per kg of milk).[25] If lower resource efficiencies and/or lower milk yields per cow are recorded in Southern and Central Eastern Europe, the net positive impact on EU-level premature mortality would be dampened. On

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[22] And affect processing and distribution activities to a lesser extent.

[23] Total employment in agriculture in the EU-28 is in excess of 10 mln.

[24] The RL pathway has the advantage that the upfront investment costs are lower and the practice of slaughtering or exporting cattle is relatively easy to scale-up in a short time-span, while building a large biogas digestion and distribution infrastructure in the livestock sector will have a considerable lead-time.

[25] Given the considerable differences per Eu region in annual average milk yields per cow (this can vary from 2.000 to up to 9.000 kg milk/y), the relative differences in environmental impact per unit of dairy can be considerable.

Table 10
Change in % compared to total $PM_{2.5}$-related premature deaths in Benelux in baseline.

Change relative to baseline		%		
		Benelux	Rest of world	Net change
RL	L-SE	−9.61%	−5.04%	−14.65%
	L-CEE	−9.63%	3.05 %	−6.57%
IMM	L-SE	−4.53%	−2.38%	−6.91%
	L-CEE	−4.53%	1.45 %	−3.08%

Results are approximate and should not be interpreted in an absolute way. For more detailed information, more extensive work would be needed in order to check the location of the farms, and compare it with the population distribution around those farms. For reasons of comparability, all percentages are relative to the baseline premature deaths in the Benelux, also in case of mortality in the rest of the world.

top of that, a displacement of cattle herds within the EU of such magnitude would put an additional strain on local resources (e.g. land, feed) and could generate a series of side-effects similar to those documented in this paper for the Netherlands.

4. Discussion & conclusions

The purpose of this research is to identify and quantify key (positive and negative) side-effects or impacts of low emission transition pathways in the livestock sector. We find that the ex-ante determined combination of simulation models used was not always suitable to meet our impact assessment needs that evolved throughout the stakeholder consultation process. We used additional off-model quantifications to partially address this issue. However, we observe that even with a broader suite of (integrated) assessment models we might not have been able to assess the full spectrum of relevant side-effects at a meaningful level of disaggregation. With respect to the latter, despite the clear positive or negative changes observed, the results from E3ME modelling were not very pronounced at the macro-economic level. This could suggest a limited economic impact of the transition pathway at the national level. At the same time, the qualitative analysis shows that the pathways will have a profound and structural impact at the sector level, e.g. in terms of type of farming (pland or animal), land use, biodiversity, air quality, etc. Depending on the specific transition pathway designs and the impacts of interest, we recommend that for the modelling work a meaningful level of (dis) aggregation is determined (i.e. macro-level, sector level, company level). This could imply the use of a broader and more diverse suite of simulation models for transition pathway analysis. While the challenge of proper model selection remains - and a more flexible and adaptive approach for model selection might be needed - we consider our mixed methodological approach with qualitative and quantitative elements useful to better assess the impacts of transitions.

Based on the results from the off model quantifications, we can observe that the IMM pathway outperforms the RL pathway in terms of renewable energy production and net domestic GHG emissions impact (FOOD scenario). However, this is without considering any displacement of cattle farming to other regions. The E3ME modelling results show that the IMM pathway has less extreme positive and negative outcomes relative to the RL pathway. This suggests that the investments in IMM facilities combined with a more modest reduction of the cattle herd dampens potential co-benefits and trade-offs at the national level. The results from the TM5-FASST model suggest that a displacement of cattle farming to other regions within the EU result in a net reduction in terms of premature mortalities at the global level. From this we can derive that displacement of cattle farming could have a positive impact on human health, while at the same time causing a net increase in global GHG emissions. This could occur when lower food conversion and production efficiencies apply in the regions where cattle farming expands (i.e. more emissions per kg of milk or meat). Such a dilemma where local benefits can result in a trade-off at the global level (or vice versa) has implications for global and local level policy making as well as the social acceptance for transitions. This dilemma could benefit from a more consensus based or participatory approach in transition management where the selection of appropriate low emission technologies and pathway design (i.e. through co-creation), tries to find an acceptable balance between the different co-benefits and trade-offs.

One could conclude from the modelling that under the IMM + FOOD scenario for the Netherlands there is a potential for achieving considerable domestic environmental and health related benefits (i.e. significant reduction in premature mortalities) at relatively modest macro-economic costs (minimal loss of GDP). However, given that we have not been able to include all potentially relevant side-effects in our analysis, such as carbon leakage (i.e. *limited scope*) we recommend caution in drawing such major conclusions in this type analyses. For example, we have not taken into account the spatial and operational implications of the IMM pathway which requires construction of ≈13.000 IMM plants in a relatively short period. We also have not quantified the carbon sequestration impact as well as any biodiversity gains related to expanding forest area (FLOWER scenario). To be comprehensive within this type of assessments we recommend a stakeholder driven / participatory approach and determine ex-ante a meaningful scope to include those side-effects in the analysis that are valued most within a diverse group of relevant stakeholders that are relevant or specific for the country or region.

While we have explored the side-effects of two distinct transition pathways in the livestock sector for the 2015-30 period, we have not assessed their ‘compatibility’ with future post 2030 GHG mitigation ambitions and trajectories. Avoiding technology lock-in, path dependency and technology compatibility will be relevant objectives for short-term transition policy strategies to stay on track to meet long-term goals. Developing transition pathways with end-emissions in mind can be helpful to avoid lock-in and promote the implementation of no-regret solutions.

We conclude that each transition pathway design has its own unique footprint of positive and negative impacts, and that these impacts can be valued differently by stakeholders, depending on stakeholder knowledge, preferences and the regional (development) context. We consider this relevant for climate policy making where the challenge is to find the optimal mix of technologies and practices and design pathways that meet multiple environmental, social and economic development objectives (i.e. to optimise co-benefits and minimize trade-offs). We anticipate that pathways that are co-created (or co-designed) with relevant stakeholder groups have a better chance of being implemented.

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