UNIVERSITY OF Southampton

Anaerobic digestion system

Energy balance

Dr Yue Zhang

VALORGAS

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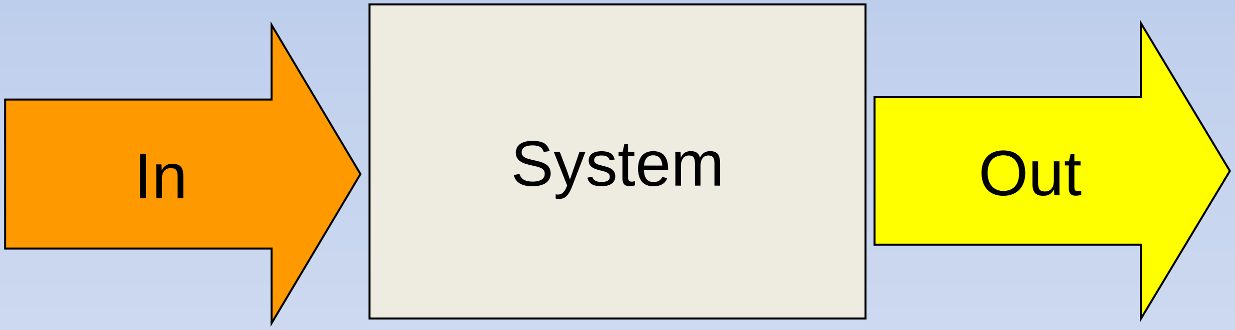
The energy balance

- Energy balance $E_b = E_{out} - E_{in}$
- E_{out} = Useful energy leaving the system
  - Energy value of fuel produced
  - Electrical, heat or mechanical energy produced
  - Energy value of by-products
- E_{in} = Energy required in the system
- Energy ratio $E_r = \frac{E_{out}}{E_{in}}$

System boundary

System boundary

- Need to identify what goes in
- What comes out?



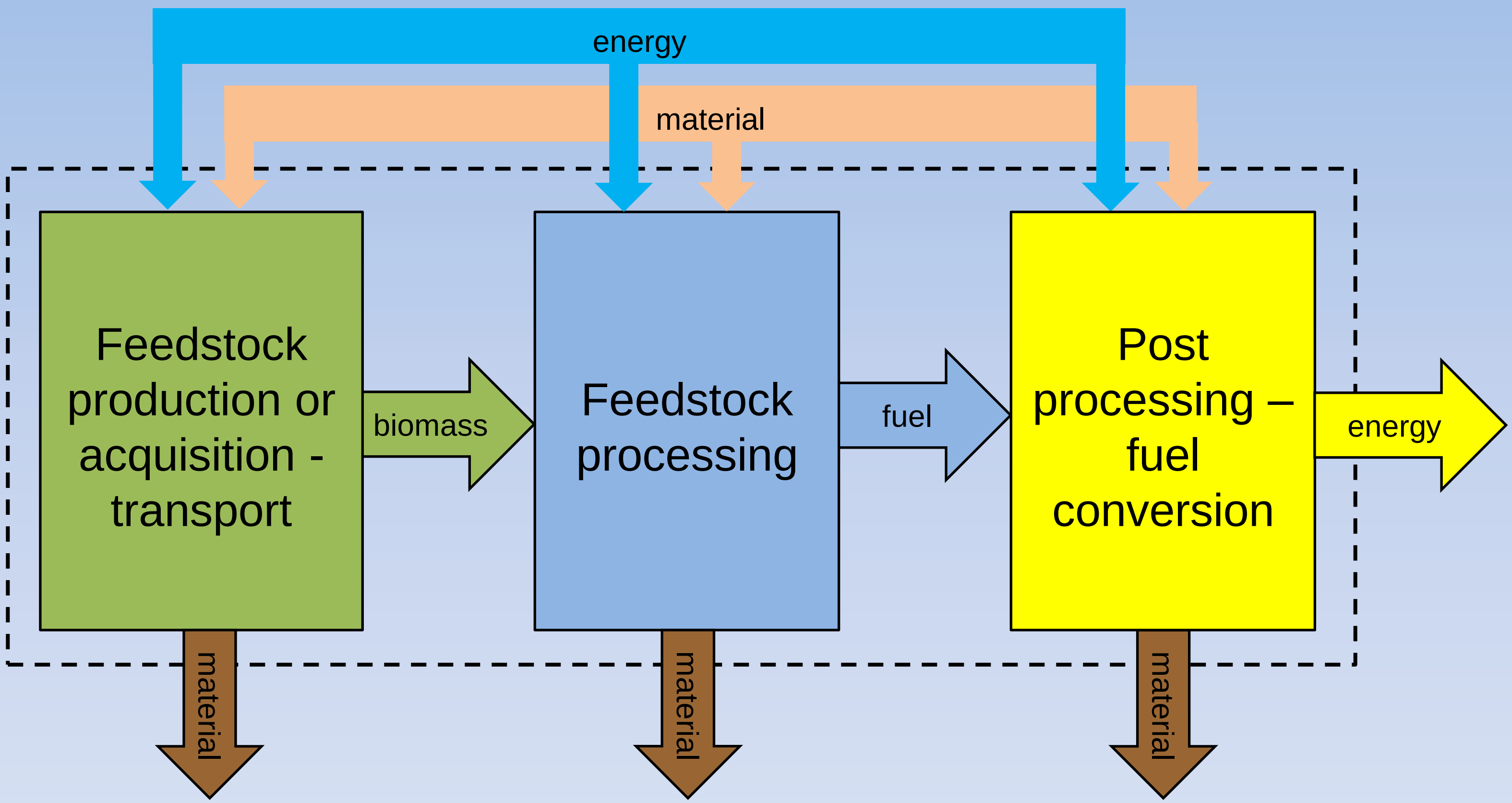
Bioenergy system

A bioenergy system will usually have the following components:

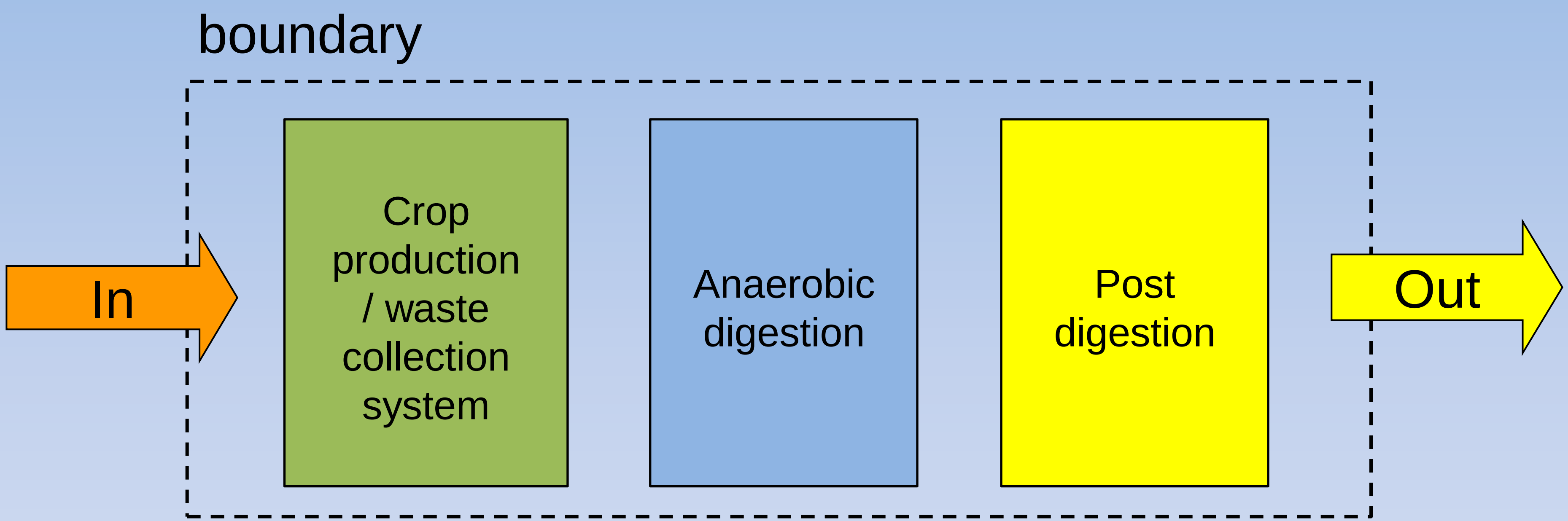
- Biomass production or cultivation
- Biomass harvesting / collection
- Biomass transport
- Biomass pre-treatment or preparation
- Biofuel production
- Biofuel purification
- By-product management
- Biofuel transport
- Biofuel use

Energy balance
&
Life cycle assessment

Three phases of bioenergy production



A general system on AD



Direct and indirect energy

Direct energy

- Energy consumed as fuel
- Consumption of energy directly in the production process, including:
  - Fossil fuels
    - Diesel or petrol in vehicles
    - Electricity for motors
    - Gas, oil or coal for heating
  - Labour

Indirect energy

- Energy required to produce equipment, includes:
  - extraction of raw materials
  - processing of materials into parts
  - construction
  - delivery
  - maintenance
  - Repair
- Crop based systems have large associated indirect energy impacts:
  - Pesticides
  - Herbicides
  - Fertilisers

Indirect energy element in direct energy

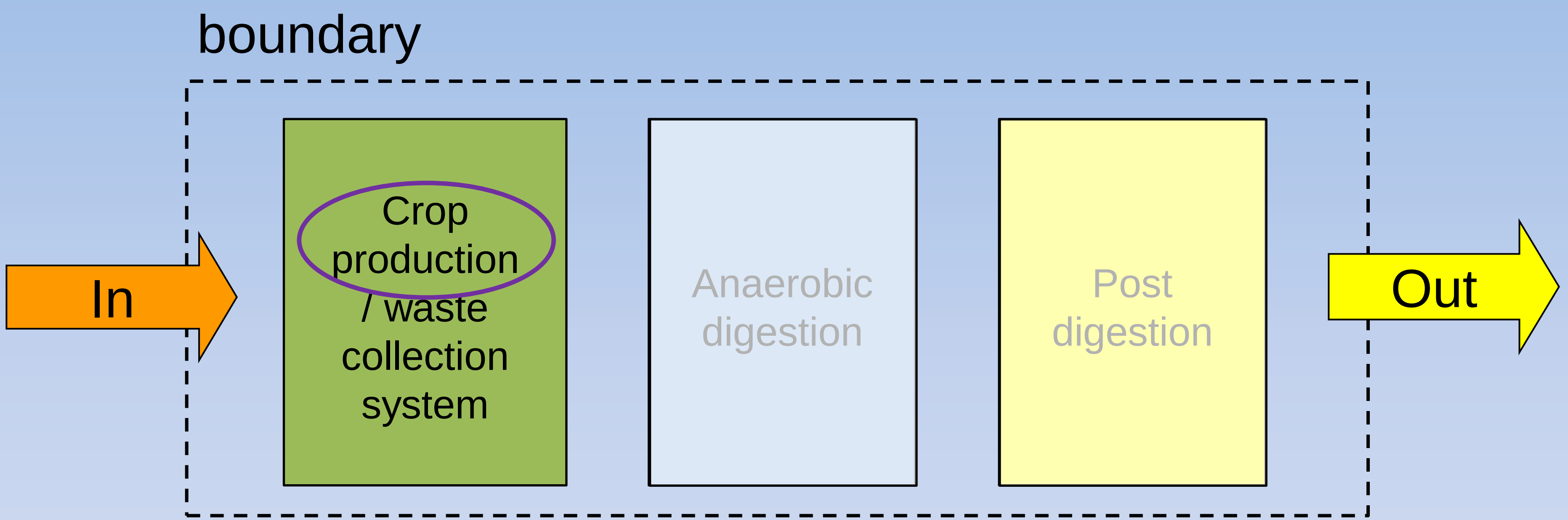
- Direct energy does not spontaneously appear
- Energy is required
    - to extract fossil fuels
    - to build generating stations and fuel processing plants
- Thus each unit of direct energy has an attached amount of indirect energy which can be expressed as a percentage of the energy value

Direct fuel source	Indirect requirement
Petroleum products	11%
Natural gas	11%
Coal	1.3%
Electricity	308%

Reference: Howard, Edwards & Anderson (1999) BRE Methodology for Environmental Profiles of Construction Materials. DETR

Feedstock production or acquisition

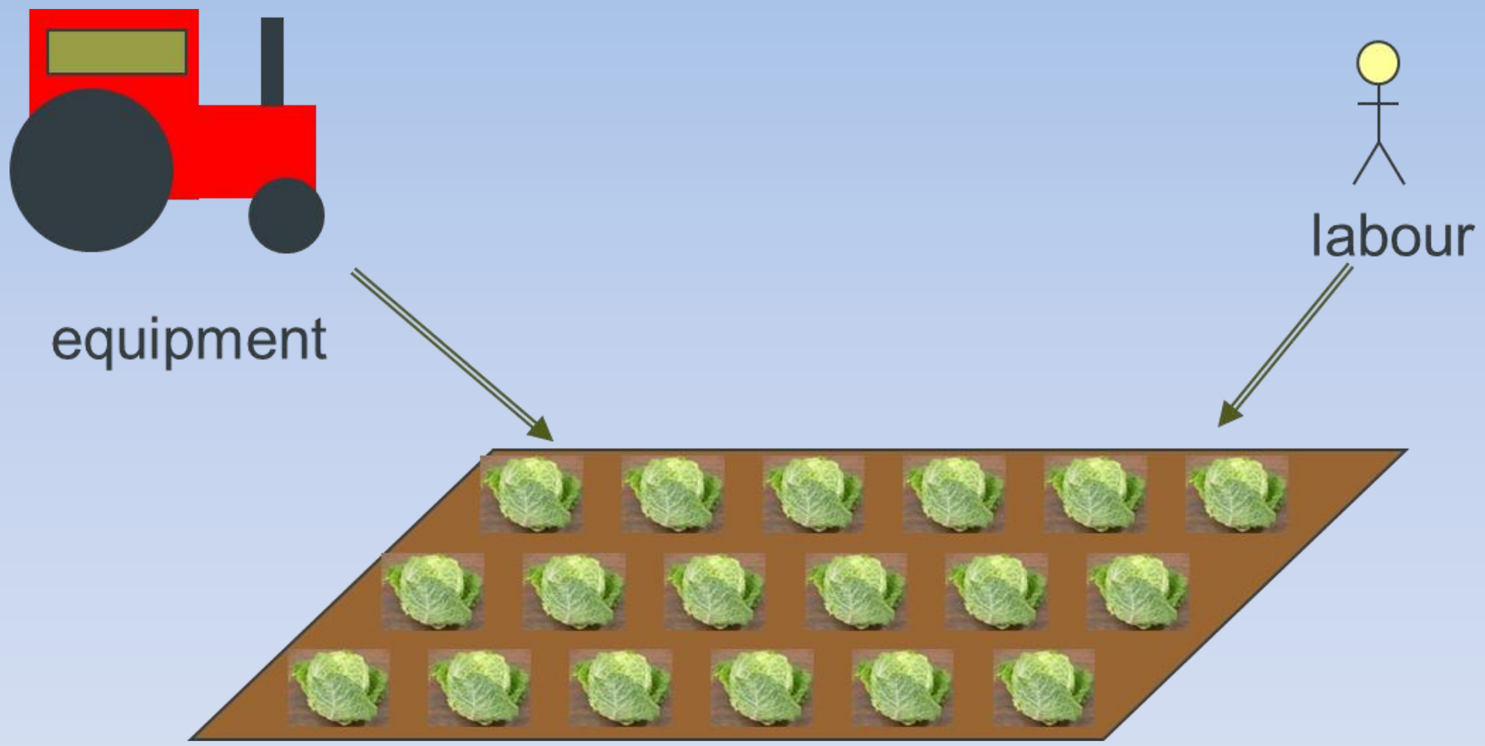
A general system on AD



Stages in growing an energy biomass

- Land cultivation
  - ploughing
  - secondary cultivation
- Sowing / drilling
- Crop maintenance and growth
  - nutrients
  - pesticides/herbicides
  - irrigation
- Harvest

Energy in crop production (1)



Field operations

ploughing

spray/fertilise

harvest

cultivations

drill/sow

Field operations – direct energy inputs

Example

Operation	ha hour^{-1}	Fuel l ha^{-1}
Ploughing	0.6	19.6
Secondary operations	1.6	6.42
Drilling	2	3.93
Rolling	3	1.3
Fertiliser application	1.6	1.99
Harvest (cereals)	1	14.62
Transport harvest	3	1.3

Adapted from Leach G. (1976) Energy and Food Production, IPC Science and Technology Press

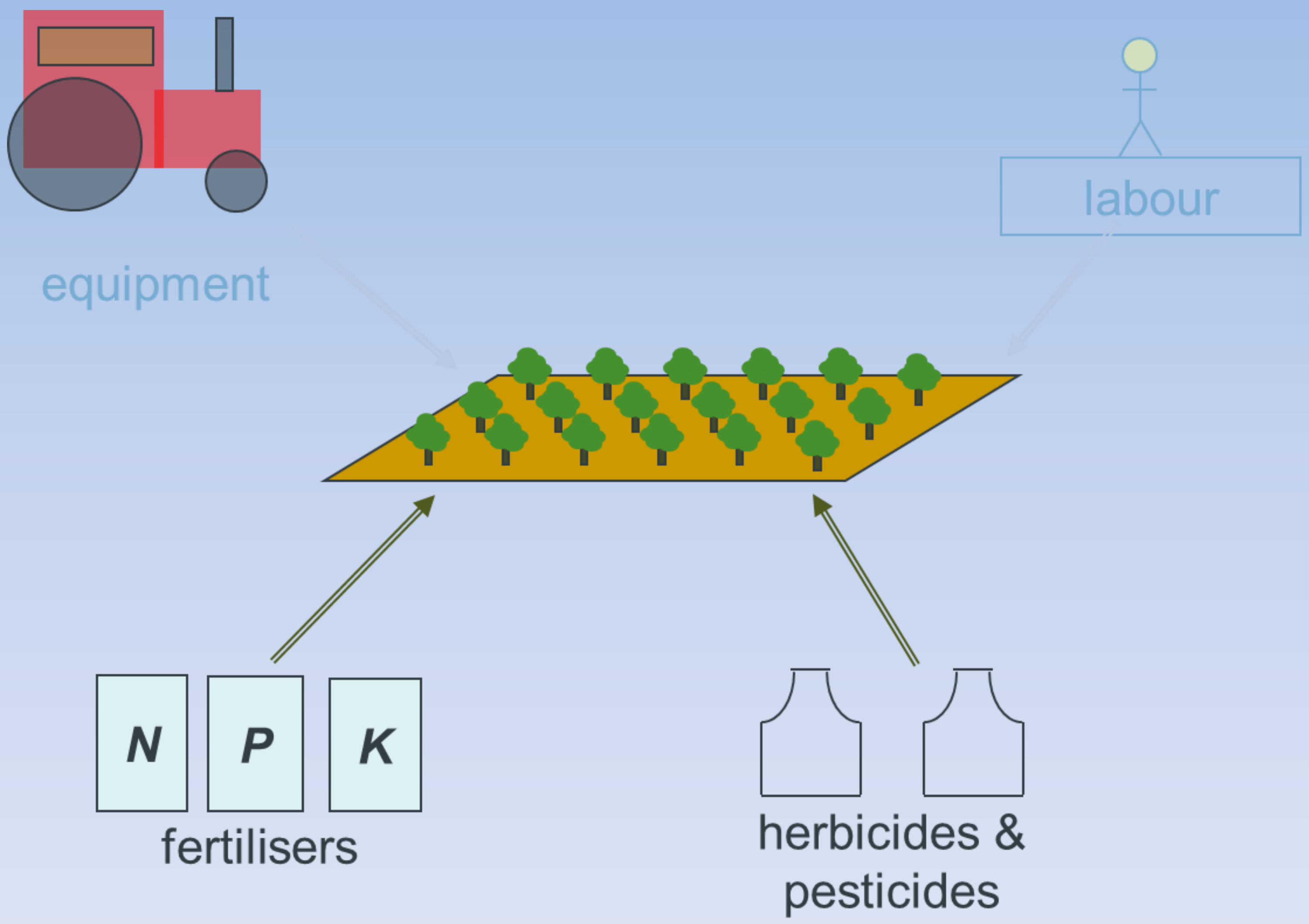
Machinery – indirect energy inputs

- Energy requirement for extraction the materials, construction and delivery
- Machinery depreciates over time and requires servicing and maintenance.
- All these can be allocated an energy value calculated over the expected working life of the equipment.

Example

Equipment	Indirect energy cost
Tractor (37.3 kW)	51 MJ hr^{-1}
Tractor (67.2 kW)	125.6 MJ hr^{-1}
Plough 5 furrow	121 MJ ha^{-1}
Drill	66 MJ ha^{-1}

Energy in crop production (2)

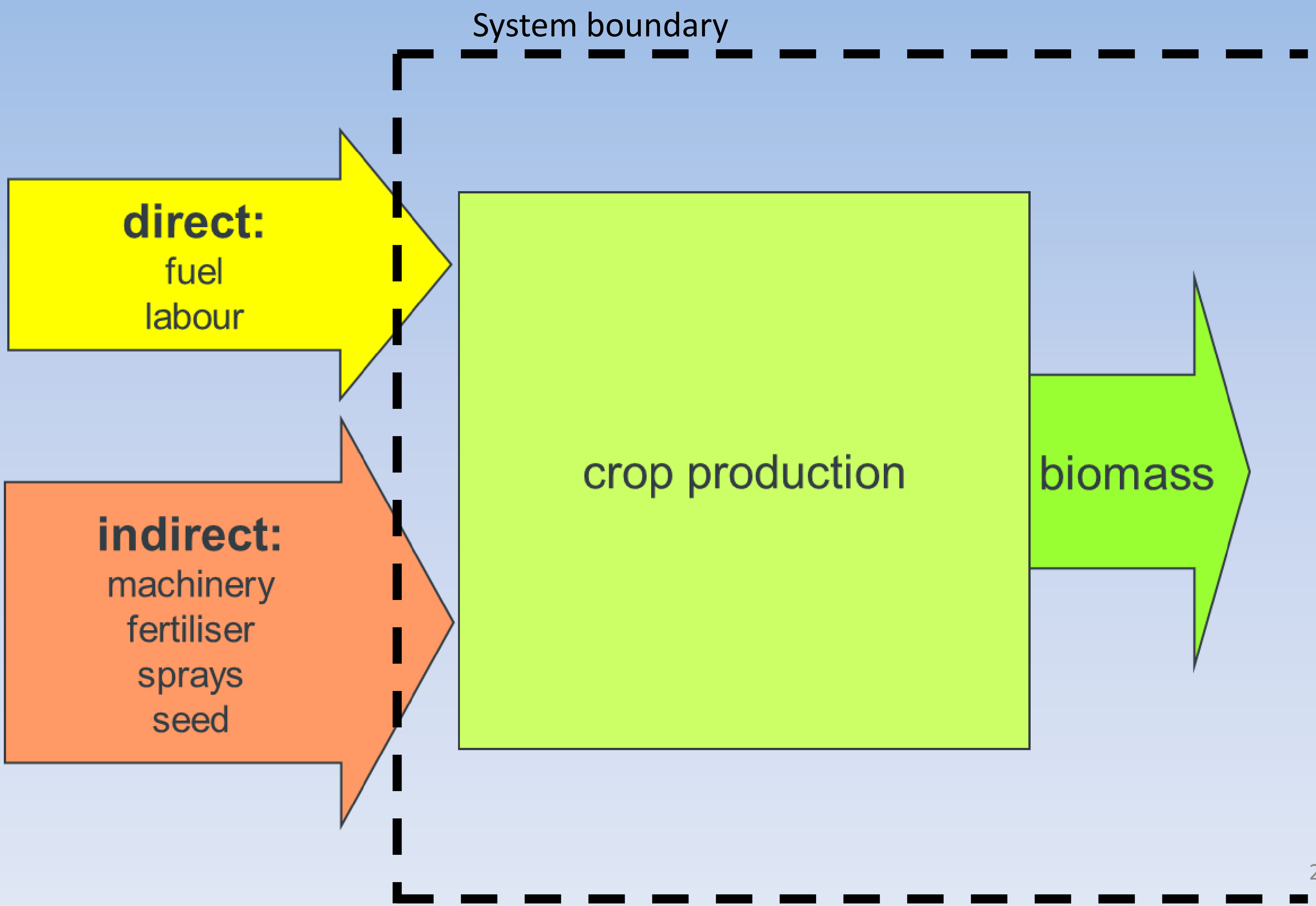


Fertilisers – indirect energy

	World consumption (million tonnes)	Specific energy (GJ $tonne^{-1}$)	Total energy consumed (million GJ yr^{-1})	Total CO_2 eq. emissions (million tonnes CO_2 eq. yr^{-1})
Nitrogen (N)	83.1	47.4	4079	261
Phosphate (P_2O_5)	31	4.7	146	10
Potassium (K_2O)	20.8	5.6	117	8

Adapted from Jenssen T. K. and Kongshaug G. (2003) Energy consumption and greenhouse gas emissions in fertiliser production. Proceedings No. 509. International Fertiliser Society. York, UK.

Crop production energy inputs

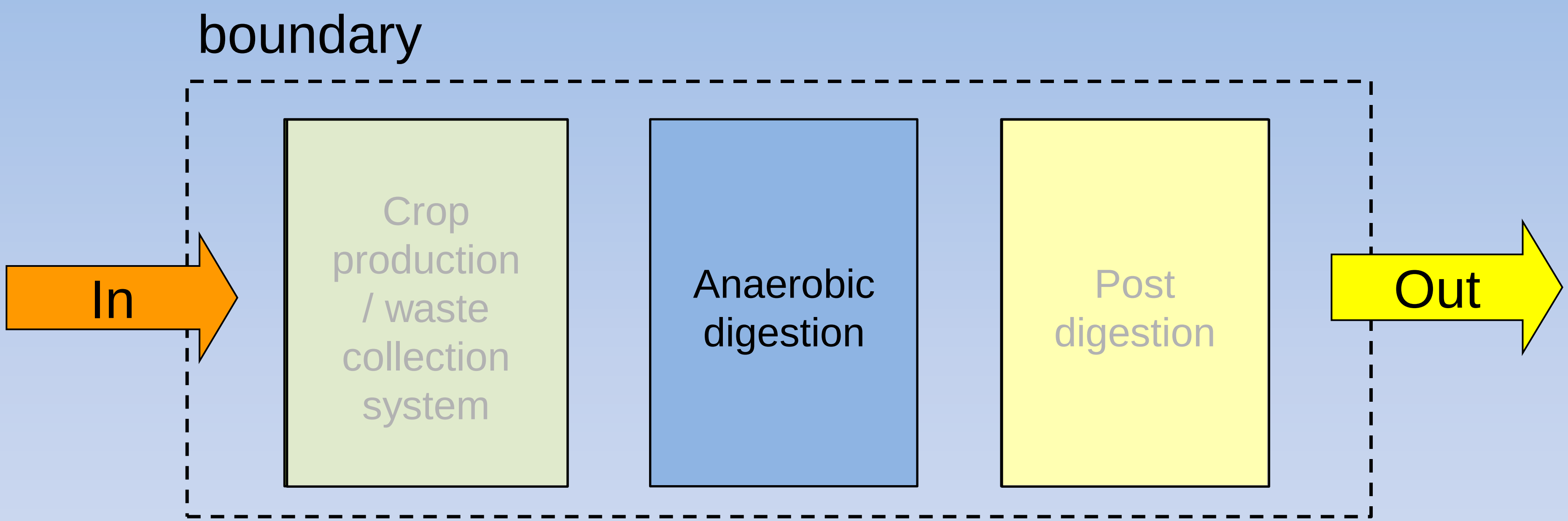


Waste collection energy inputs

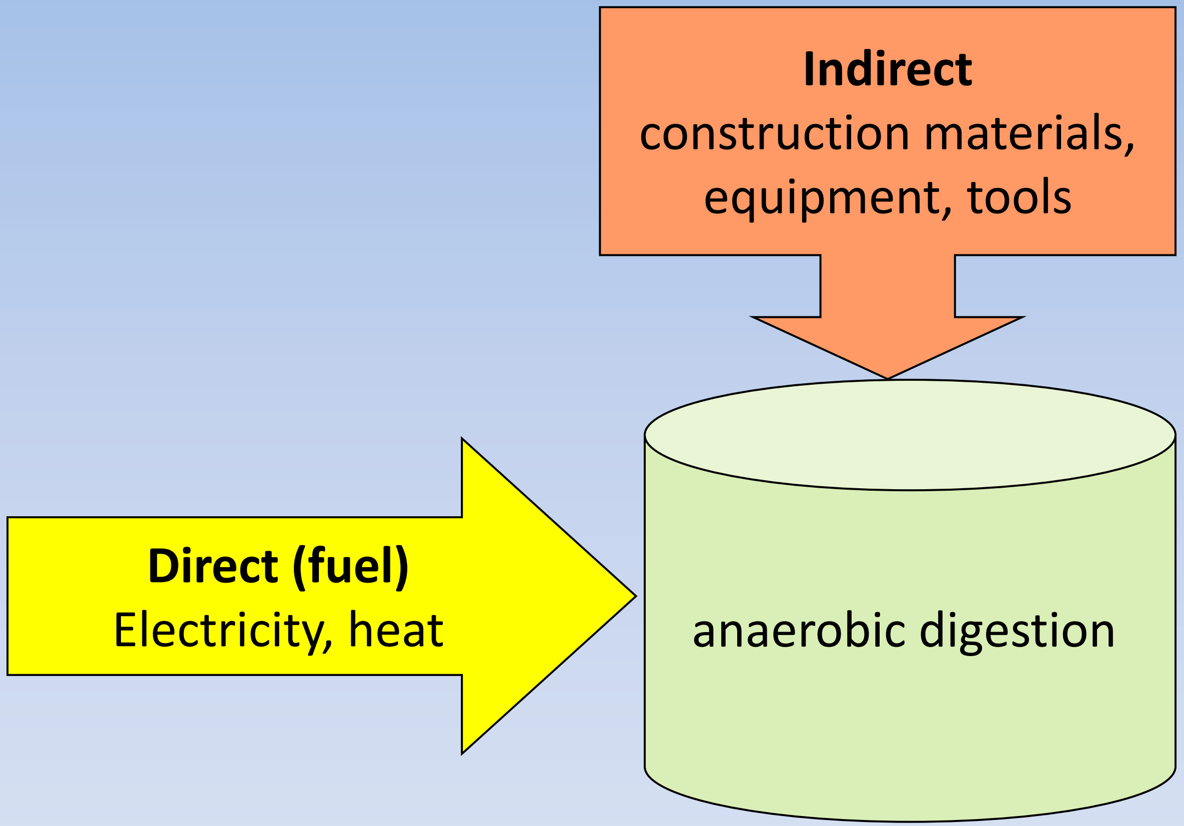
- Fuel, labour, and vehicles used in waste collection system
- Sometimes the energy involved is discounted in the calculation as waste has to be collected anyway

Anaerobic digestion

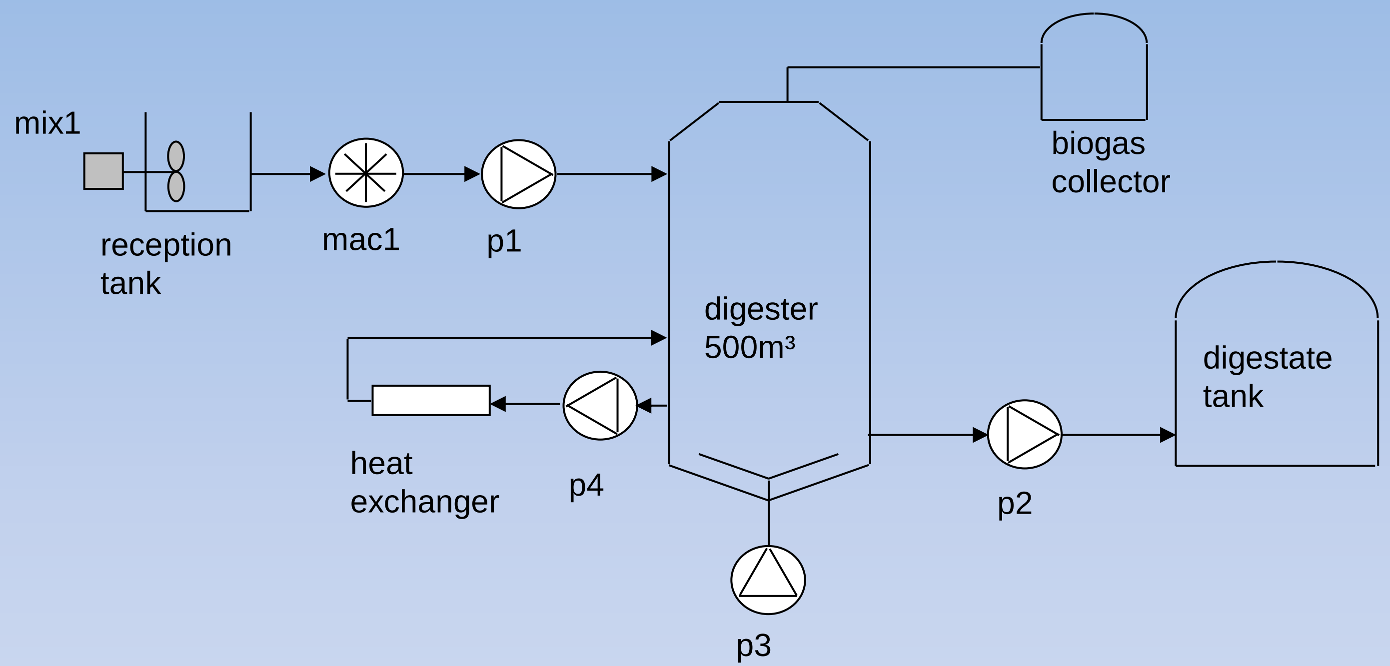
A general system on AD



Anaerobic digestion - Energy inputs



Electricity requirement

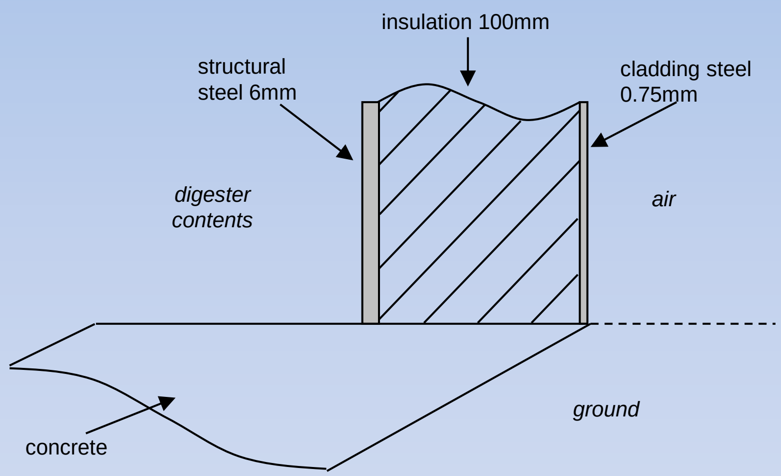


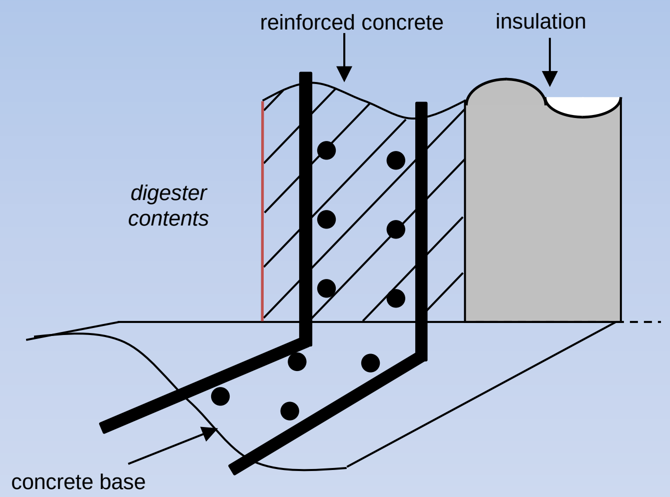
mix1	reception tank mixer	3.0 kW	0.64 hrs/day
mac1	feedstock macerator	2.2 kW	1.75 hrs/day
p1	digester feed pump	3.0 kW	1.75 hrs/day
p2	digester discharge pump	3.0 kW	1.75 hrs/day
p3	digester mixing pump	2.2 kW	7.25 hrs/day
p4	digestate heating pump	0.5 kW	8.0 hrs/day

Heat requirement

- Two sources of heat requirement:
  - Heat loss from walls, floor and roof of digester
  - Heat to bring feedstock material up to digester temperature

Digester wall construction





Heat loss

Heat loss (hl) = $UA\Delta T$ (kW)

where

U = overall coefficient of heat transfer, W m^{-2} $°C^{-1}$

A = cross-sectional area through which heat loss is occurring, m^2

ΔT = temperature drop across surface in question, °C

structure	heat transfer coefficient (W m².°C)
Concrete wall 300mm thick, not insulated (above ground)	4.7 - 5.1
Concrete wall 300 mm thick, insulated (above ground)	0.6 - 0.8
Concrete floor 300mm thick (in contact with dry earth)	1.7
Fixed concrete cover 100mm thick and covered, 25 insulation	1.2 - 1.6
Floating cover with 25mm insulation	0.9 - 1.0
6mm steel plate 'sandwich' with 100mm insulation	0.35

Heat loss example

- Walls:

  hlw = 0.8 W m^{-2} °C^{-1} × (132 m^2) × (35 - 2 °C) = 3.48 kW

- Floor:

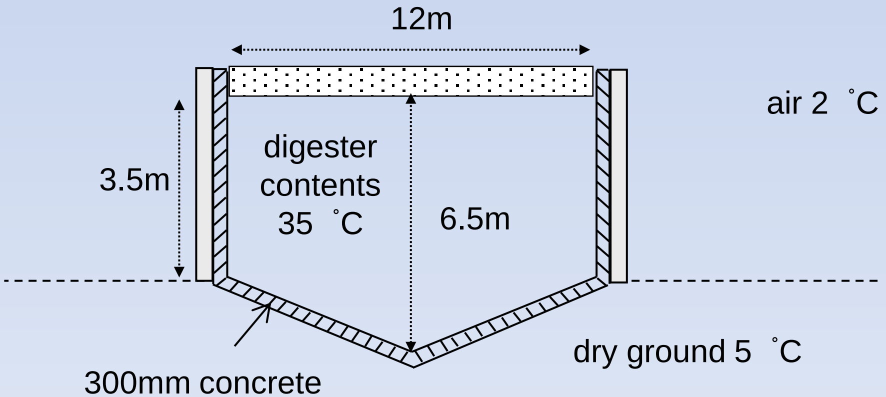
  hlf = 1.7 W m^{-2} °C^{-1} × (126 m^2) × (35 - 5 °C) = 6.43 kW

- Roof:

  hlr = 1.0 W m^{-2} °C^{-1} × (113 m^2) × (35 - 2 °C) = 3.73 kW

- Total heat loss:

  hl = 3.48 + 6.43 + 3.73 = 13.64 kW = 1.18 GJ day^{-1}



Heating of feedstock

- Feedstock added to the digester must be brought up to the operating temperature of the digester
- *Heat required = CQΔT*

where:

C = specific heat capacity of feedstock (MJ $tonne^{-1}$ $°C^{-1}$)

Q = volume to be added (m^3)

ΔT = temperature difference (°C)

- Example:

A $500m^3$ digester running at 35 °C with a retention time of 30 days

- Volume added (Q) = 500 / 30 = 16.7 m^3 day^{-1}
- Specific heat capacity (C) = 4.2 MJ $tonne^{-1}$ $°C^{-1}$
- Feedstock temperature = 10 °C
- Heat required = 4.2 × 16.7 × (35 - 10) = 1.75 GJ day^{-1}

Total heat requirement

- Total heat requirement = heat loss + heat for feedstock
- May be supplied by external heat via heat exchangers
- May be provided by self heating within the digester (e.g. exothermic reaction)
- Example

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Finland	3.52	3.35	3.27	3.18	2.76	2.37	2.16	2.06	2.42	3.03	3.22	3.33
UK	3.07	3.07	2.88	2.59	2.31	2.02	1.83	1.83	2.11	2.10	2.79	2.88

Anaerobic digestion - Indirect energy

- Construction materials
- Construction

Material	Energy requirement (GJ $tonne^{-1}$)
Concrete	4.9
Construction steel	35
Plastics	87
Construction energy	3.4% total embodied energy

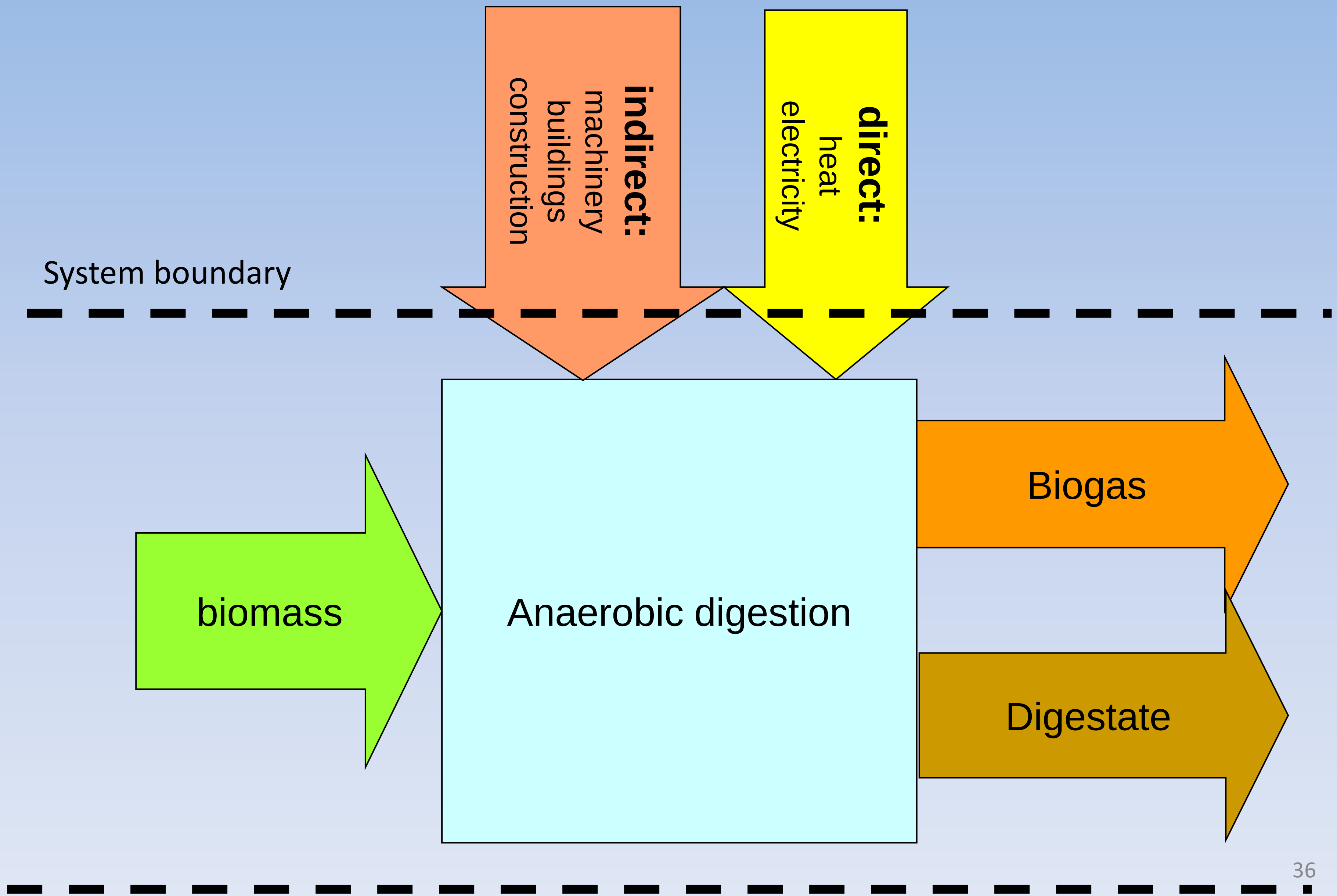
References:
Alcorn (1996) Embodied Energy Coefficients of Building Materials
Elsayed, Matthews, Mortimer (2003) Carbon and Energy Balances for a Range of Biofuel Options

Plant construction

- A Austrian digester of 3000 m^3

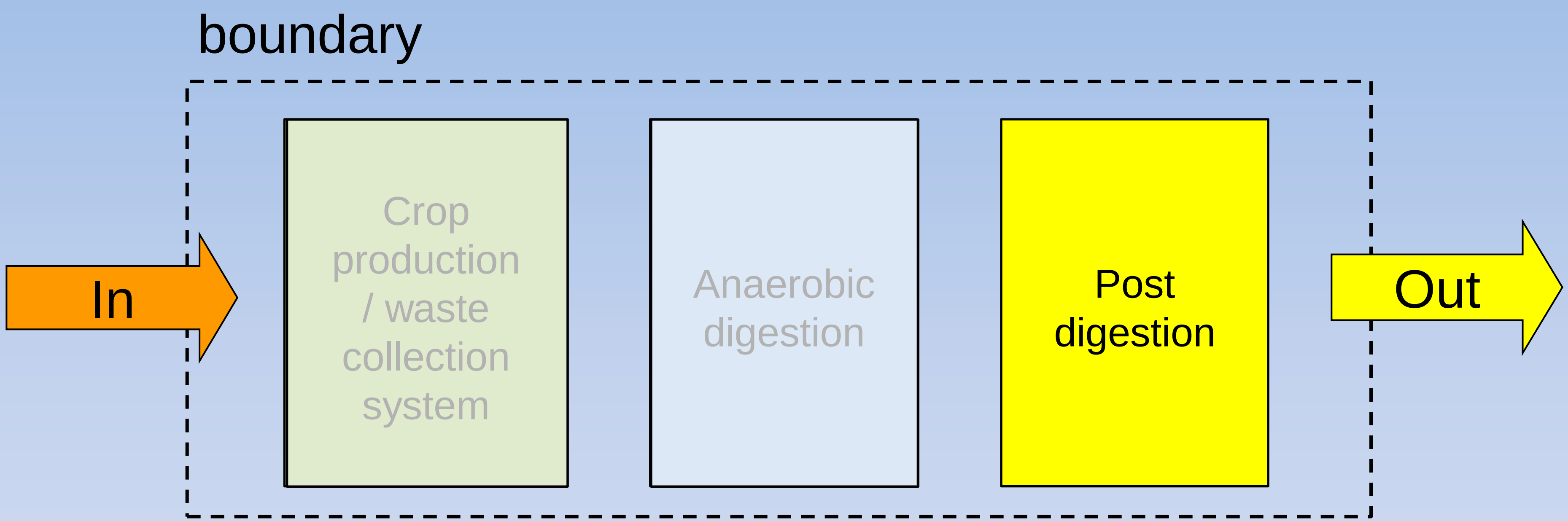
Materials	Mass (tonnes)	Energy (GJ)
Concrete	5000	24,500
Bricks	36	35
Wood	10	68
Construction steel	90	3,150
Asphalt	1000	3,236
Embodied total		32,500
Construction		1,105
Total for plant		**33,605**
Indirect energy per year (20 year life)		**1680 GJ $year^{-1}$**

Anaerobic digestion

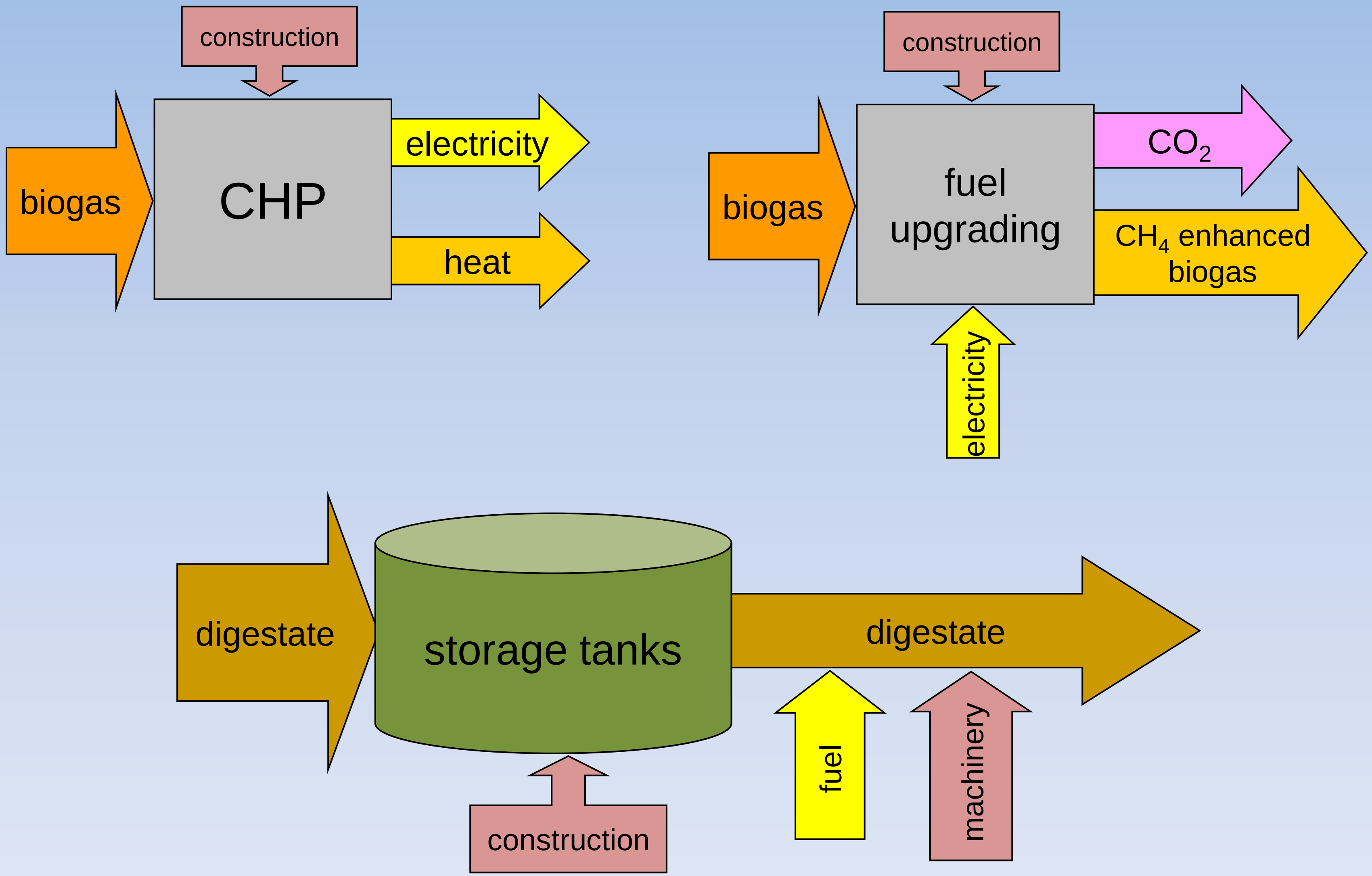


Post digestion

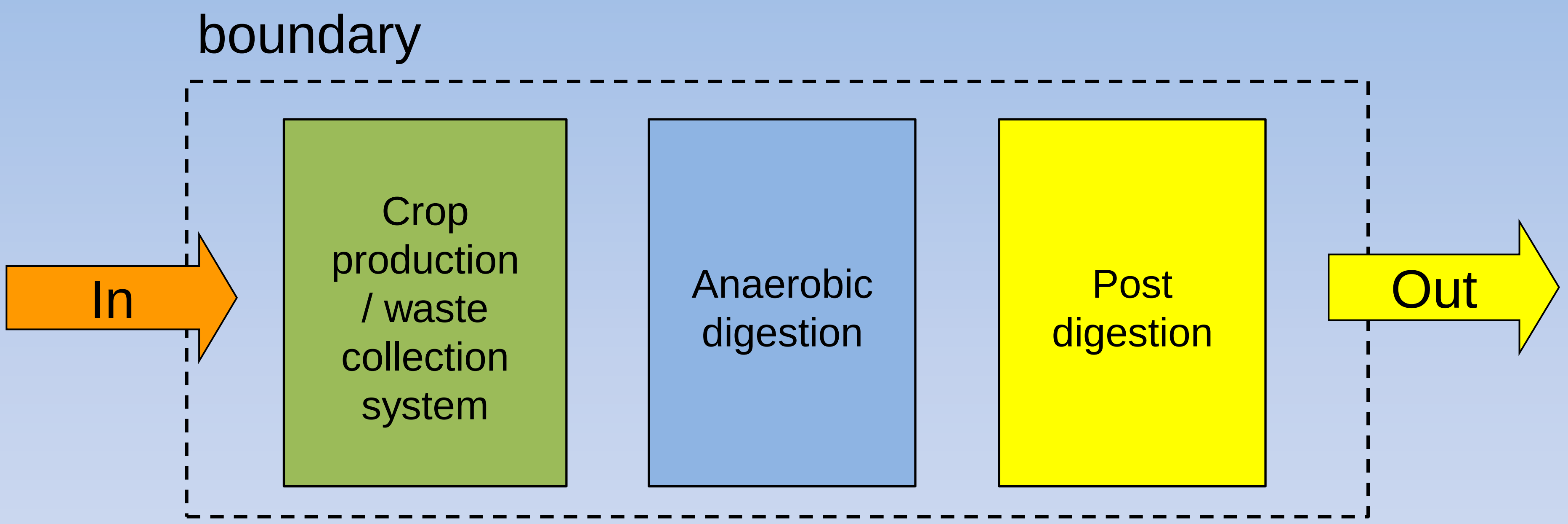
A general system on AD



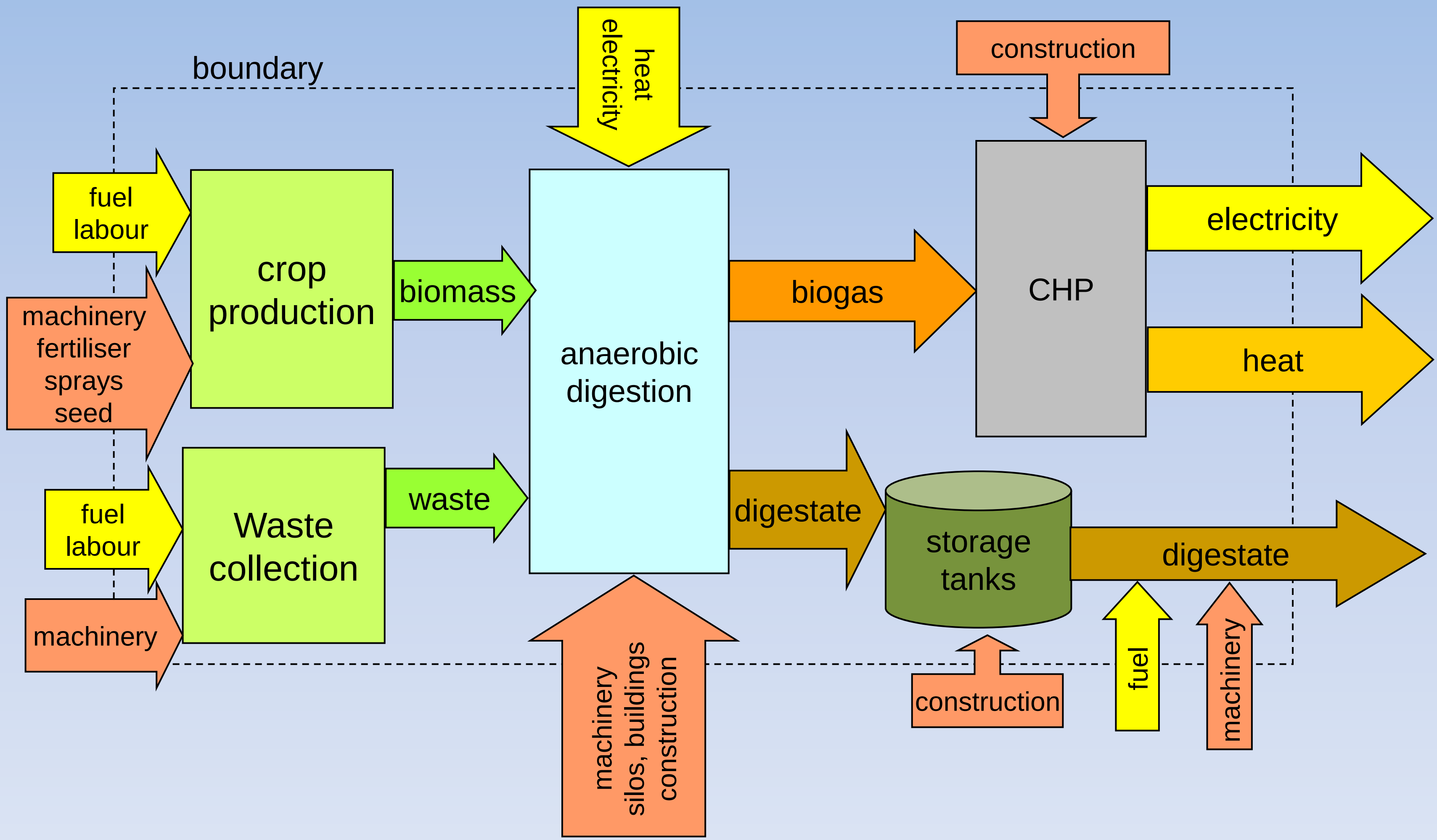
Post digestion



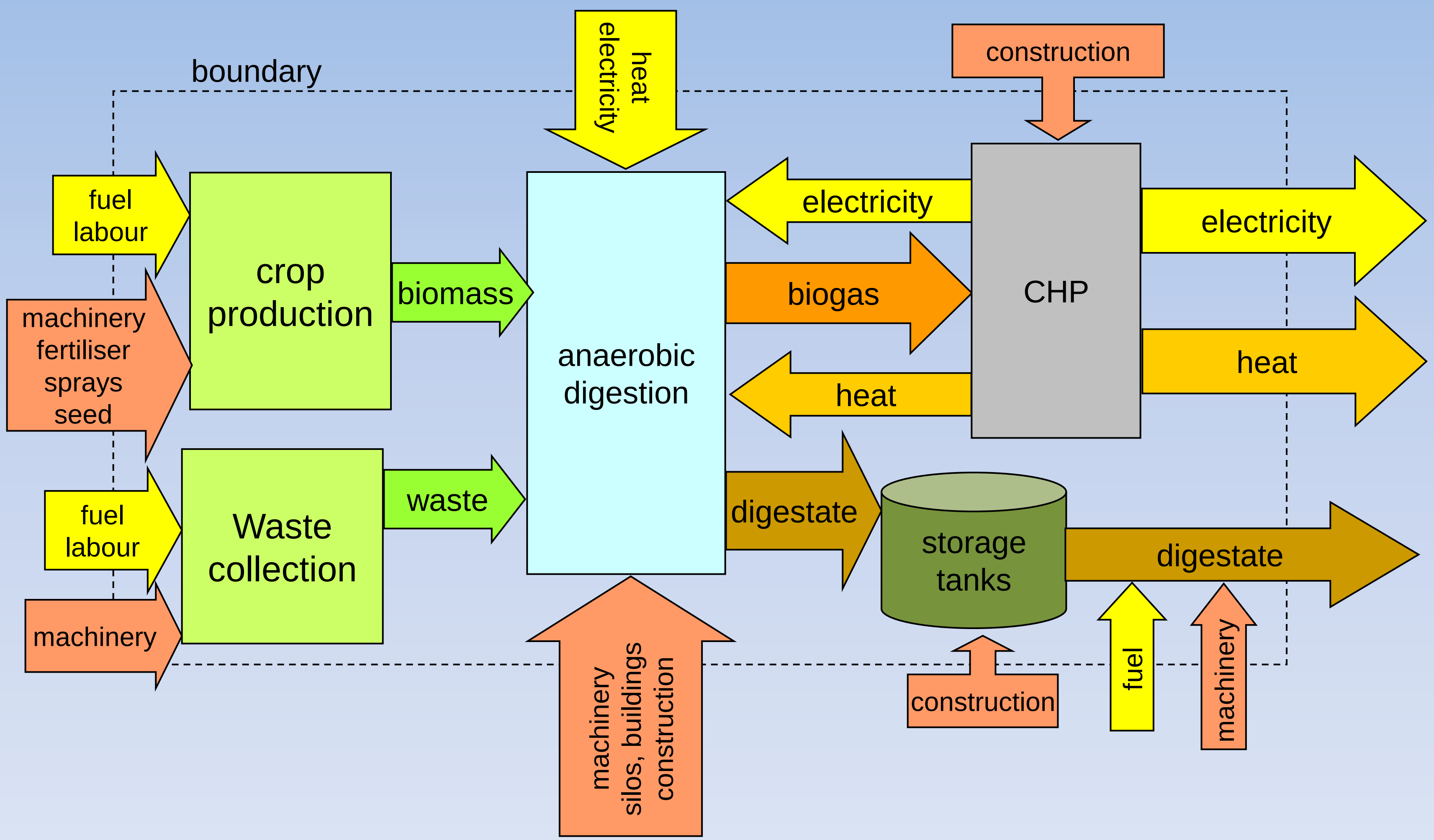
The complete system on AD



The complete system on AD



Self generated heat and electricity



Energy balance examples

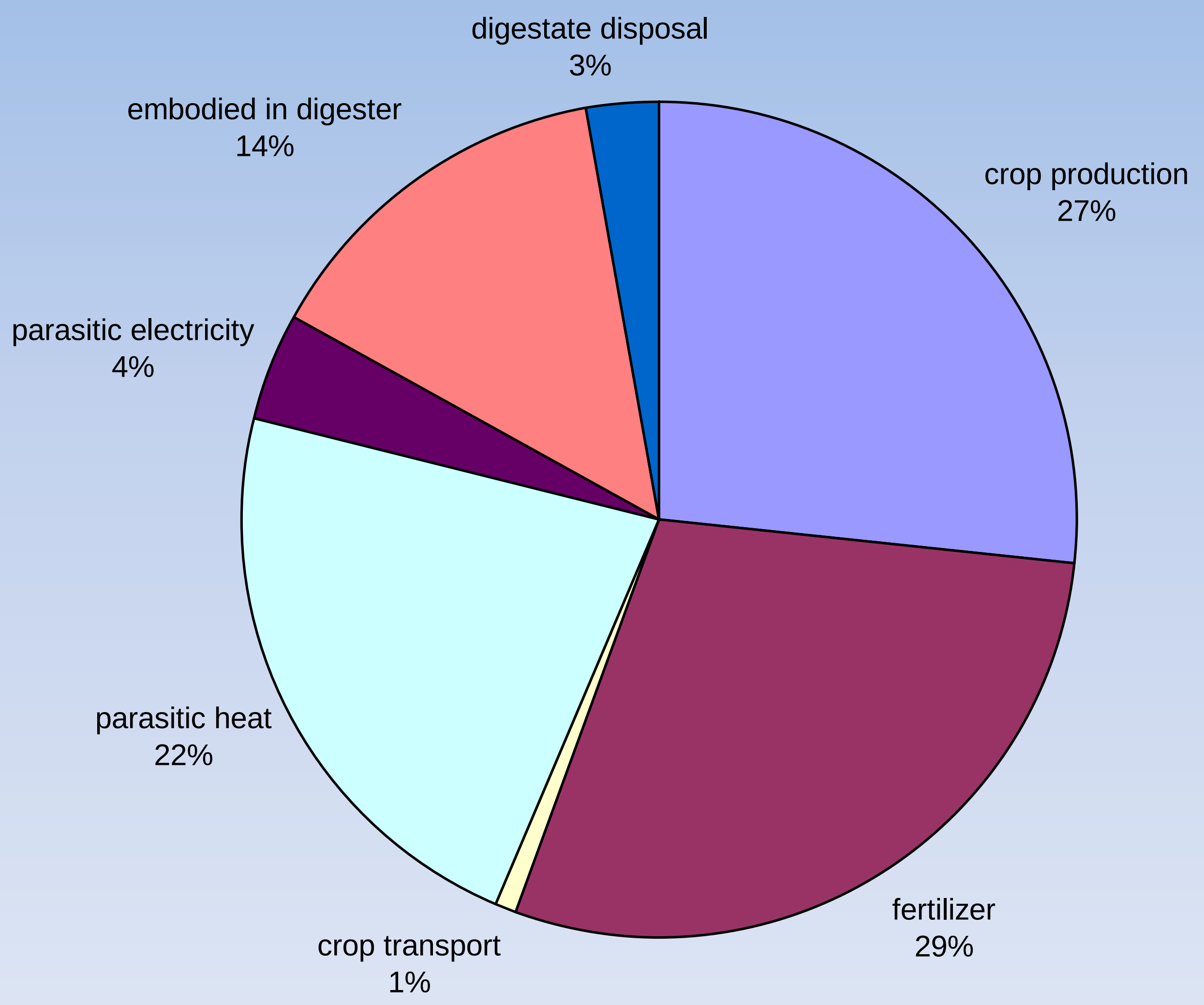
Energy balance on maize digestion

- Digester:
  - capacity = 3800 m^3
  - construction = mainly concrete
- Life expectancy of digester = 20 years
- Feedstock = single substrate (forage maize)
- CHP:
  - 30% electricity efficiency
  - 55% heat efficiency
- Climate: UK
- Fertiliser: fossil fuel based mineral fertiliser

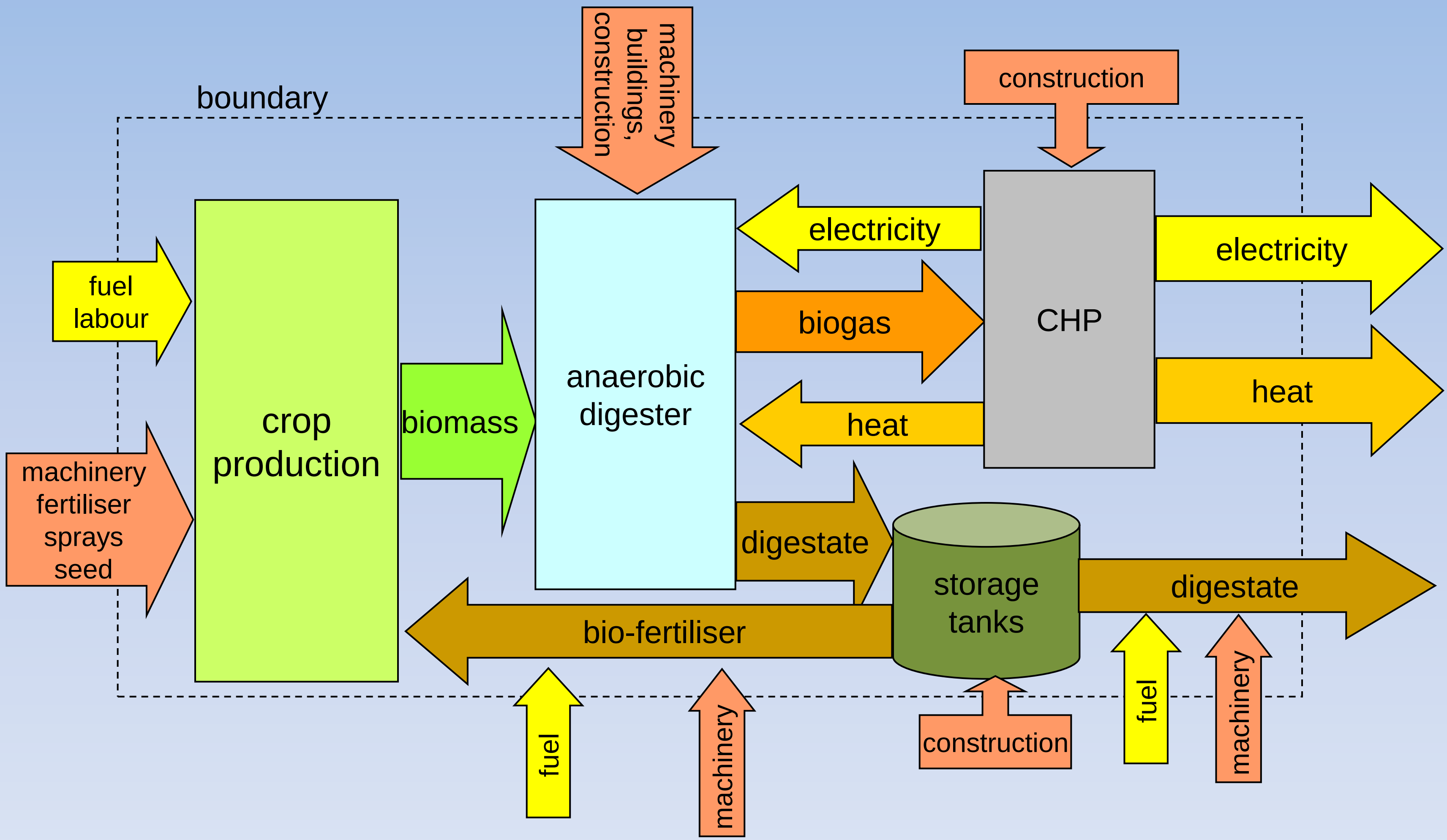
Energy balance on maize digestion

crop production (direct & indirect)	7,429	GJ $year^{-1}$
crop transport	274	GJ $year^{-1}$
digester embodied energy	2,109	GJ $year^{-1}$
digestate disposal	430	GJ $year^{-1}$
Energy into system	10.9	TJ $year^{-1}$
methane produced	1.94	10^6 m^3 $year^{-1}$
Electricity generated	20.8	TJ $year^{-1}$
Heat generated	34.7	TJ $year^{-1}$
parasitic electricity required	0.7	TJ $year^{-1}$
parasitic heat required	4.1	TJ $year^{-1}$
electrical energy out of system	20.1 (5597)	TJ $year^{-1}$ (MWh $year^{-1}$)
heat energy out of system	30.6 (8501)	TJ $year^{-1}$ (MWh $year^{-1}$)
Energy balance (E_{out} – E_{in})	39.9	TJ $year^{-1}$

Energy requirements on maize digestion



Recycling the digestate in crop production



Energy balance using digestate

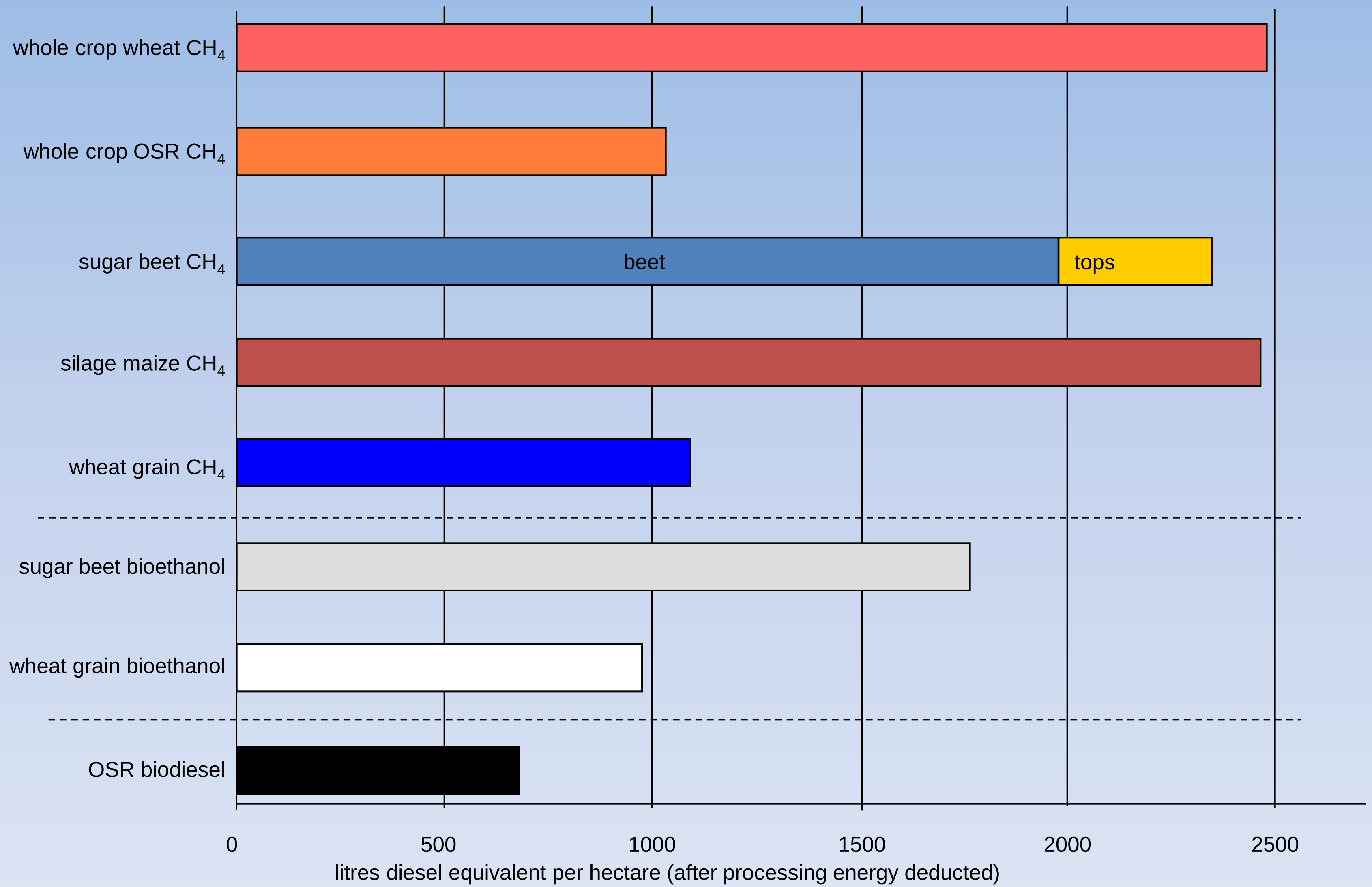
crop production (direct & indirect)	4.231 (~~7,429~~)	GJ year^{-1}
crop transport	274	GJ year^{-1}
digester embodied energy	2,109	GJ year^{-1}
digestate disposal	430	GJ year^{-1}
Energy into system	7.5 (~~10.9~~)	TJ year^{-1}
methane produced	1.94	10^6 m^3 year^{-1}
Electricity generated	20.8	TJ year^{-1}
Heat generated	34.7	TJ year^{-1}
parasitic electricity required	0.7	TJ year^{-1}
parasitic heat required	4.1	TJ year^{-1}
electrical energy out of system	20.1	TJ year^{-1}
heat energy out of system	30.6	TJ year^{-1}
Energy balance (E_{out} – E_{in})	43.2 (~~39.9~~)	TJ year^{-1}

Energy for upgrading

- Upgrading requires electricity which can come from CHP run on biogas
- Example
  - An upgrading plant consumes 0.5 kWh of electricity per m^3 of biogas upgraded
  - The CHP generates electricity with an efficiency of 30%
  - The biogas is 60% methane so it has an energy value of 6.0 kWh m^{-3} biogas
  - Electricity generated per m^3 of biogas = 6 × 30% = 1.8 kWh m^{-3}
  - % of electricity energy available consumed in upgrading

    = (1.8-0.5) / 1.8 = 28%

Production of vehicle fuel



Alternative feedstock – food waste

- No energy required for production
  - Transport
  - Digestion
- Digestate replaces mineral fertilisers
  - Energy saving of 2139 GJ $year^{-1}$
  - CO_2 saving of 153 tonnes

12000 tonnes $year^{-1}$ of food waste, 2400 m^3 digester		CHP
crop production (direct & indirect)	GJ/year	0
waste transport	GJ/year	840
parasitic electricity	GJ/year	396
parasitic heat	GJ/year	723
digester embodied	GJ/year	95
pasteuriser heat	GJ/year	3103
pasteuriser embodied	GJ/year	2
total	**GJ/year**	**5159**
energy in methane produced	GJ/year	30160
generated electricty	GJ/year	10556
generated heat	GJ/year	15080
exported electicty	GJ/year	10160
	MWh/year	2822
exported heat	GJ/year	11254
	MWh/year	3126
energy balance (E_{out} - E_{in})	**GJ/year**	**16255**

Feedstock comparison

feedstock (tonnes)	grass (16,000)	cattle slurry (16,000)	grass(8,000) + slurry (8,000)	grass(8,000) + food waste(8,000)
potential CH_4 ($10^3 m^3$)	1,759	217	988	1,578
Digestate (t/year)	13,331	15,670	14,414	13,606
parasitic heat energy (GJ/year)	2,425	2,425	2,425	4,526
parasitic electrical energy (GJ/year)	528	528	528	531
digestate transport & spreading (GJ/year)	347	407	375	354
energy for crop production (GJ/year)	6680		3340	3340
energy for crop production - recycled digestate (GJ/year)	3720		1860	1860
waste transport (GJ)				88
electricty generated (GJ)	21,979	2,711	12,345	19,717
heat generated (GJ)	34,538	4,261	19,399	30,984
energy balance (GJ/year)	**46,537**	**3,612**	**25,077**	**41,862**
energy balance - recycled digestate (GJ/year)	**49,497**	**3,612**	**26,557**	**43,342**

Digester volume: 3000 m^3

Conclusion – energy balance

- To determine an energy balance
  - Identify system boundaries
  - Account for direct and indirect energy used
    - Include energy to produce/transport the biomass
    - Energy to process the biomass into bioenergy

- If the energy balance is negative
  - It takes more energy to produce the bioenergy than is contained in the bioenergy
  - Try another biomass source or another bioenergy process