Energy Balances

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Outline

- The energy balance
- Direct and indirect energy
- System boundaries
- Crop production
- Digestion & biogas processing
- Energy produced
- Calculating an energy balance

Energy Balance

- E_{out} = Energy value of fuel produced
- E_{in} = Energy required to produce the fuel
- Energy balance $E_{bal} = E_{out} – E_{in}$

Direct energy

- Energy consumed as fuel
- Consumption of energy directly in the production process - includes:
  - fossil fuels
  - labour

i.e. diesel
electricity
gas

Indirect energy

- Energy required to produce equipment
- includes
  - extraction of raw materials
  - processing of materials into parts
  - construction
  - delivery
  - maintenance
  - repair

Direct-indirect 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 unit of indirect energy which can be expressed as a percentage of the energy value

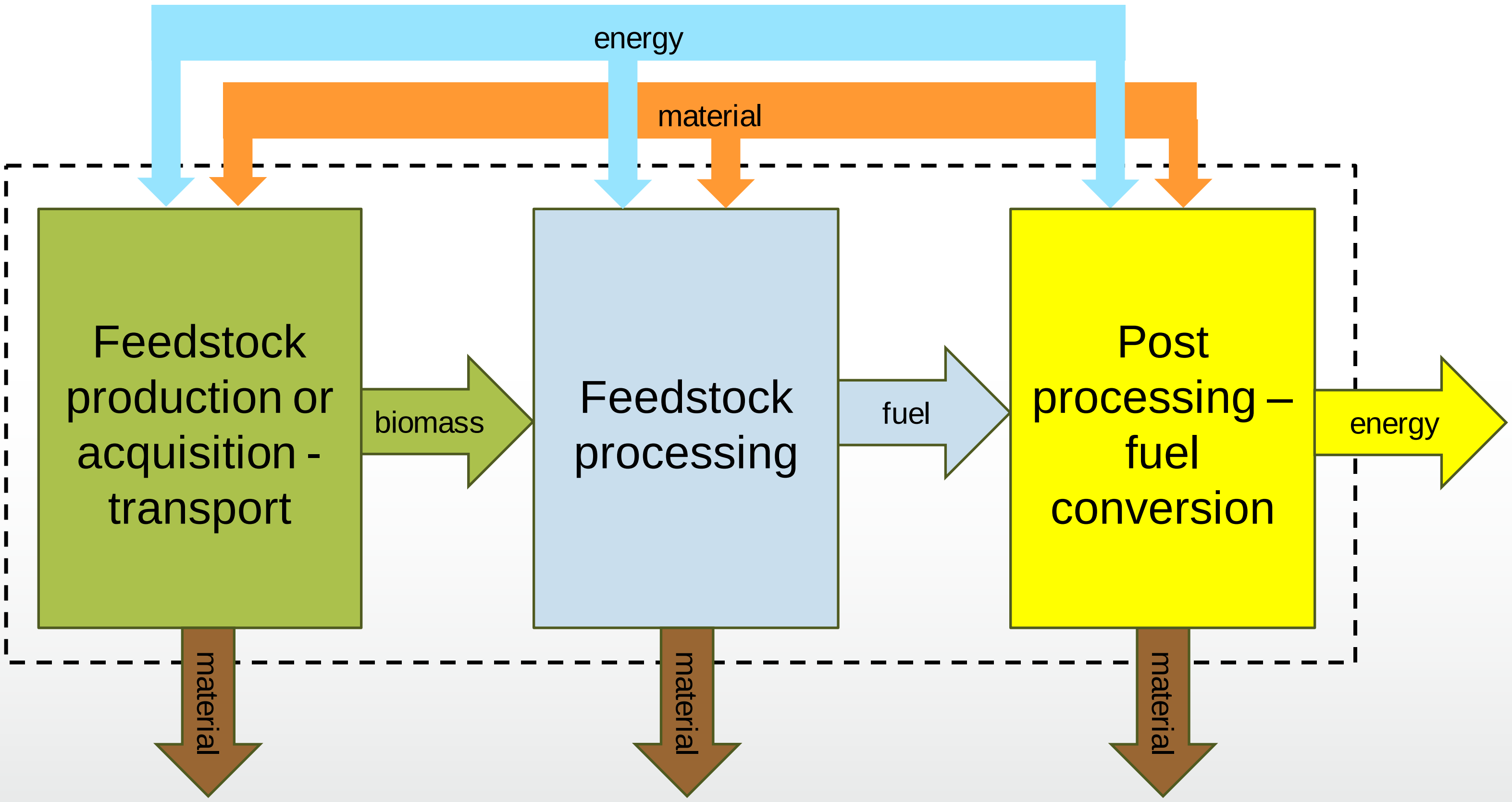
direct fuel source	indirect requirement
petroleum products	11%
natural gas	11%
coal	1.3%
electricity	308%

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

System boundaries

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

Three phases of fuel production

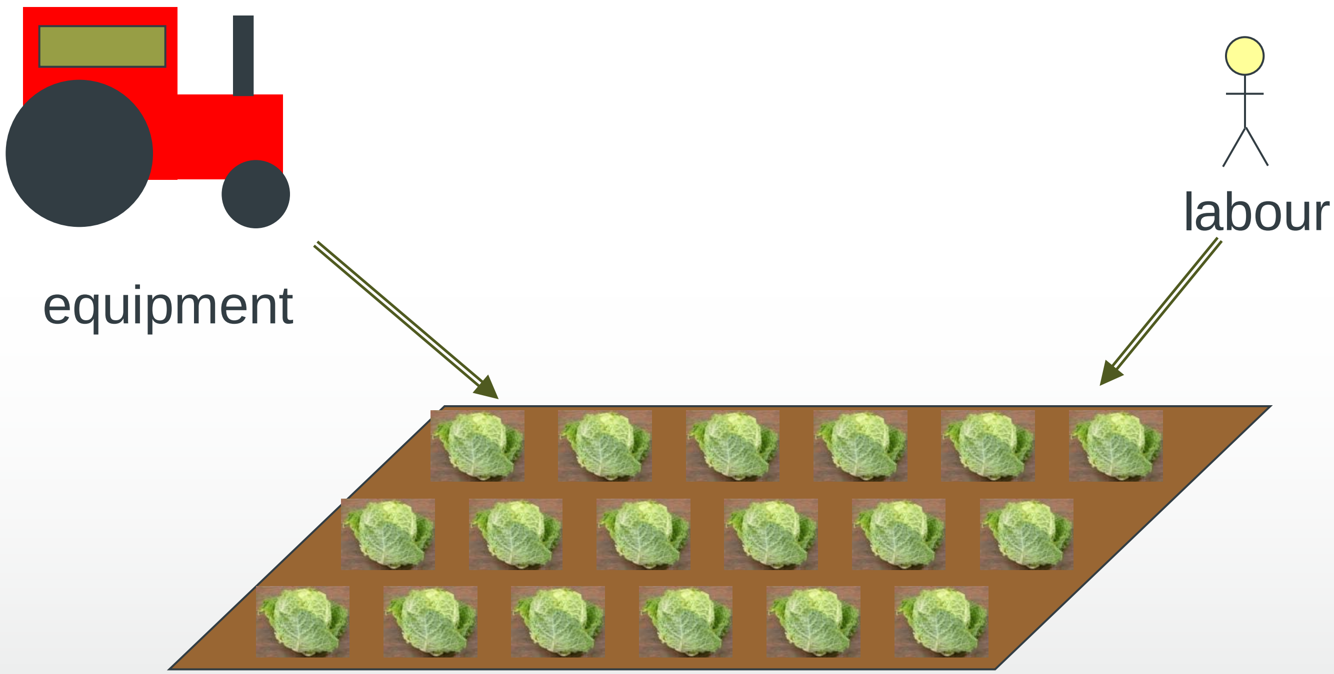


The system


boundary
In
crop production / waste collection system
anaerobic digester
post treatment
Out


boundary
In
crop production / waste collection system
anaerobic digester
CHP / upgrading
Out

Energy in crop production



Field operations

ploughing

cultivations

drill/sow

spray/fertilise

harvest

Direct & indirect inputs

	direct	indirect
cultivation	fuel	equipment
harvest	fuel	equipment
fuel		production and transport

Field Operations - direct energy

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

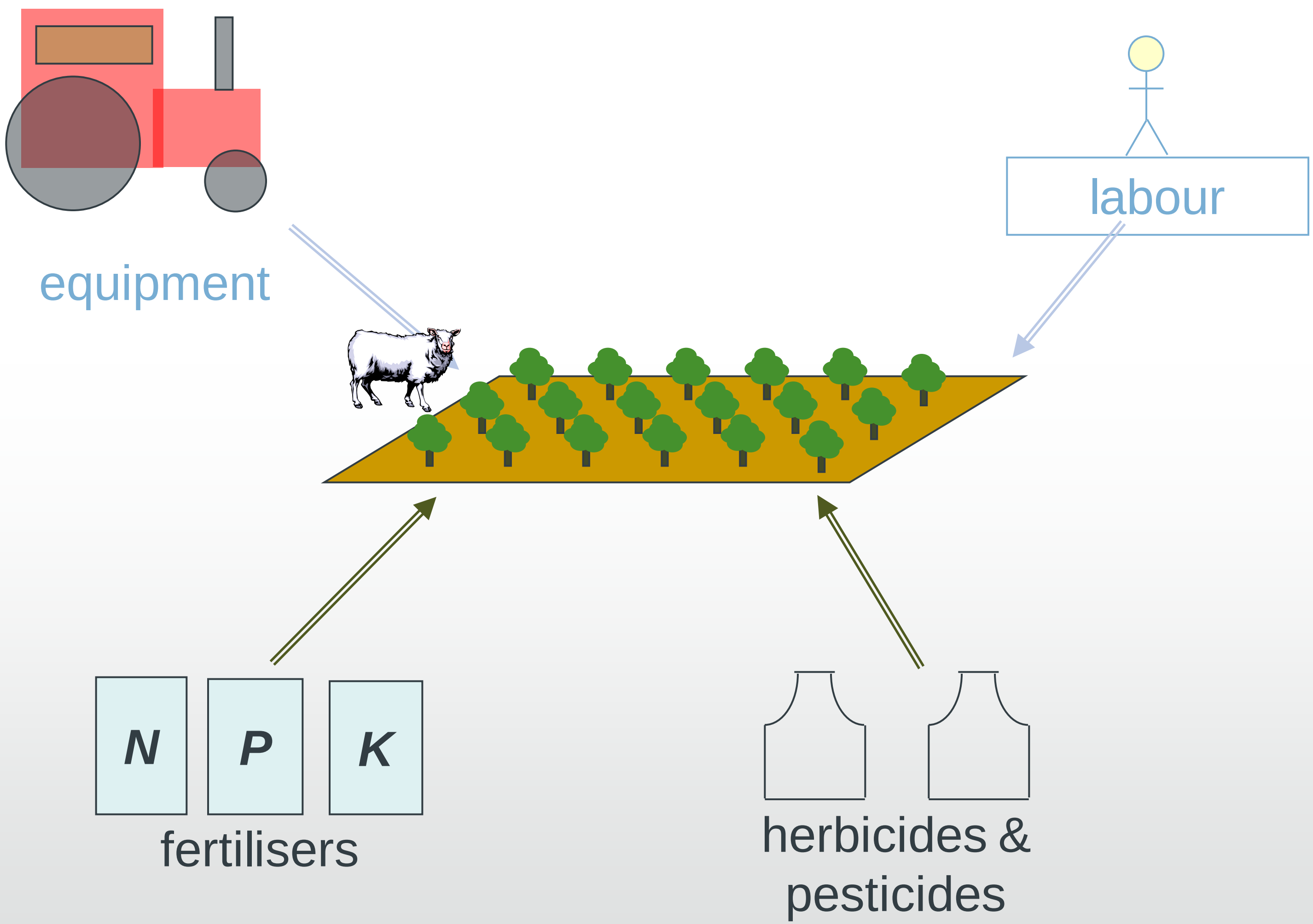
(adapted from Leach, 1976)

Machinery - indirect energy

- Machinery depreciates over time and requires servicing and maintenance.
- This can be allocated an energy value calculated over the expected working life of the equipment.
- Some equipment (tractors, harvesters) have both direct and indirect energy costs, some only indirect energy costs (plough, drill)

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

Energy in crop production (2)



Energy inputs - pesticides and fertilisers

- Direct
  - Fuel used in application
  - Labour
- Indirect
  - Fertilisers
  - Pesticides

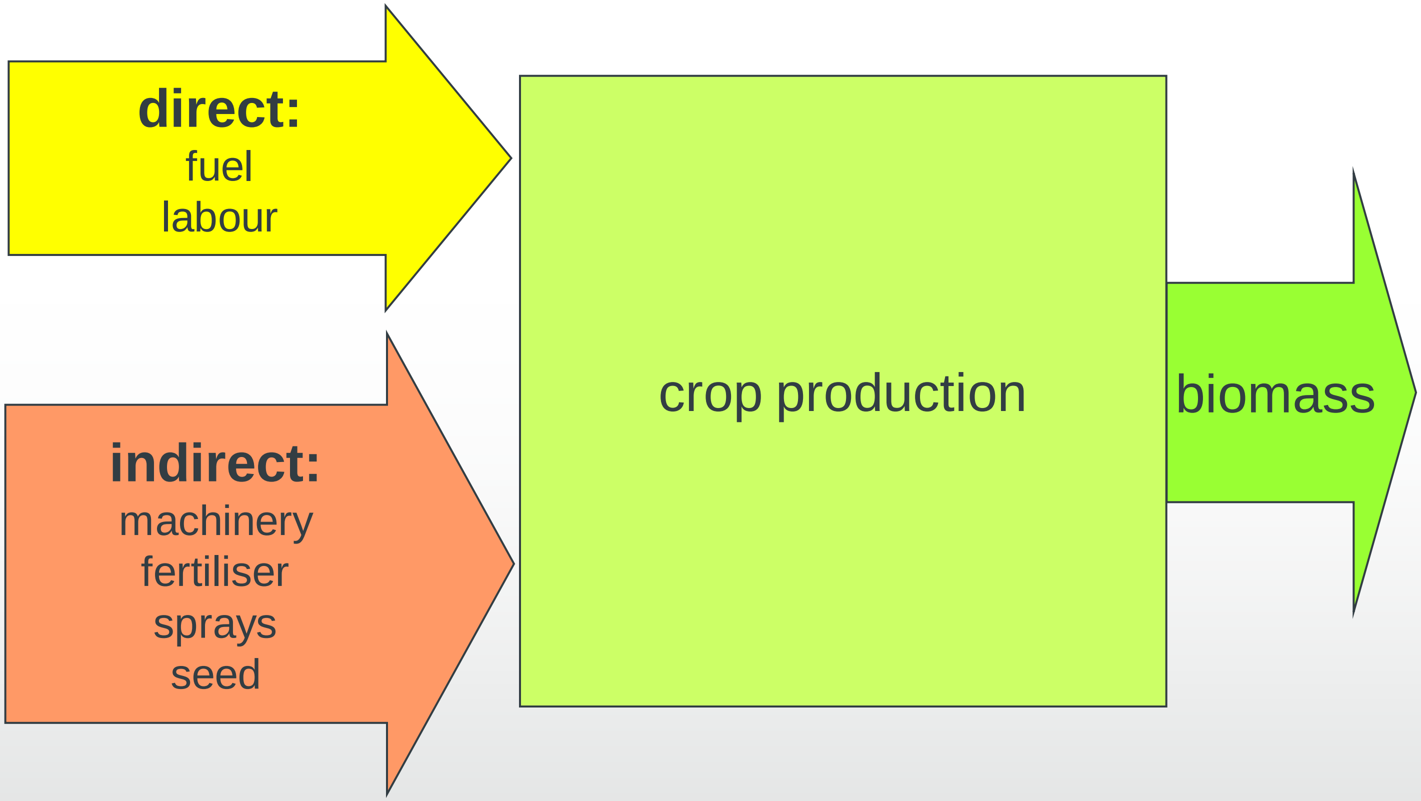
  } production and distribution
  - Machinery used in application

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 & Kongshaug, 2003)

Crop production

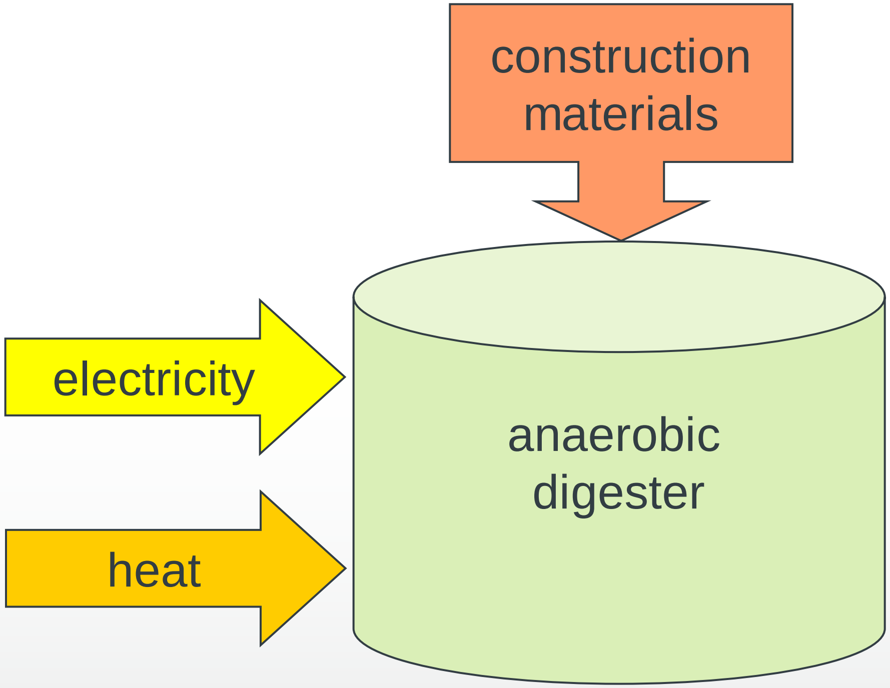


Waste collection

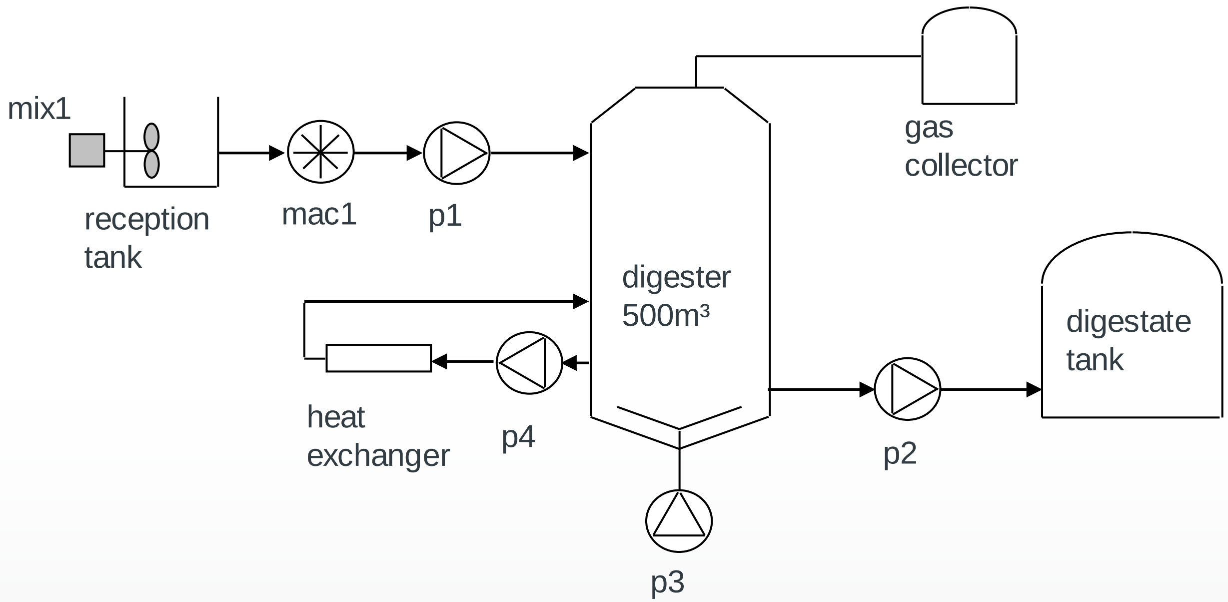
- Usually the energy involved is discounted in the calculation as waste has to be collected anyway


boundary
In
crop production
anaerobic digester
post treatment
Out

Energy inputs



Electricity requirement

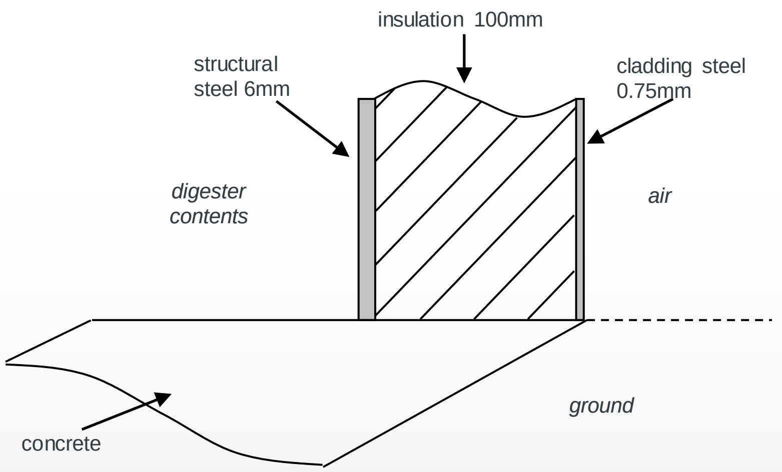


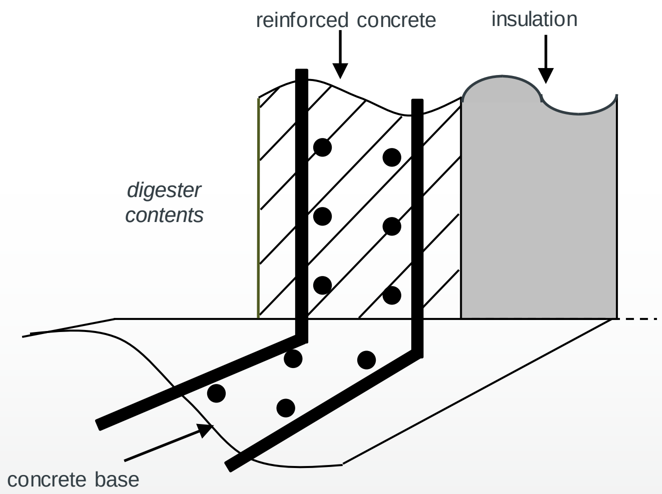
mix1	reception tank mixer	3.0 kW	0.64 hrs/day
mac1	feedstock macerator	2.2 kW	1.75 hrs/day
p1	digester feed pump	3.0 kW	1.75 hrs/day
p2	digester discharge pump	3.0 kW	1.75 hrs/day
p3	digester mixing pump	2.2 kW	7.25 hrs/day
p4	digestate heating pump	0.5 kW	8.0 hrs/day

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∆T (kW)

where

U = overall coefficient of heat transfer, ($W\ m^{-2}.\ ^{\circ}C$)

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

∆T = temperature drop across surface in question, (˚C).

structure	**heat transfer coefficient ($W\ m^2.°C$)**
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 m². ˚C * (132 m²) * (35 - 2 ˚C) = 3.48 kW

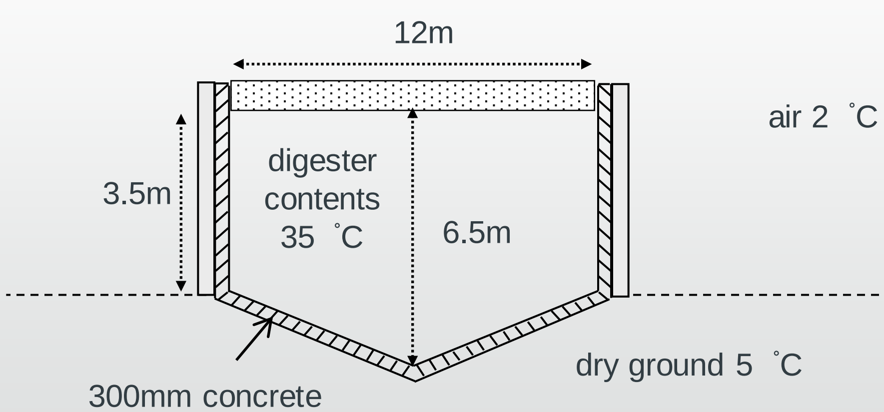
- floor:

  hlf = 1.7 W m². ˚C * (126 m²) * (35 - 5 ˚C) = 6.43 kW

- roof:

  hlr = 1.0 W m². ˚C * (113 m²) * (35 - 2 ˚C) = 3.73 kW

- Total heat loss *hl* = 13.64 kW = 1.18 GJ/day



Heating of feedstock

- Feedstock added to the digester must be brought up to the operating temperature of the digester
- *Heat required (q) = CQΔT*
- *where:*
  - *C* = specific heat of feedstock
  - *Q* = volume to be added
  - *ΔT* = temperature difference

- Thus for a 500m^3 digester with a retention time of 30 days
- volume added (*Q*) = 16.7m^3/day
- specific heat (*C*) = 4.2 MJ/tonne ˚C
- temperature feedstock = 10 ˚C, temperature digester = 35 ˚C

$$q = 4.2 * 16.7 * (35-10) = 1.75 \text{ GJ/day}$$

Heat requirement

- Total heat requirement =
  - heat loss + heat for feedstock
  - = hl + q

- May be supplied by external heat via heat exchangers.
- May be provided by self heating within the reactor.

	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

average daily heat requirements (GJ/day)

Indirect energy

- construction materials
- construction

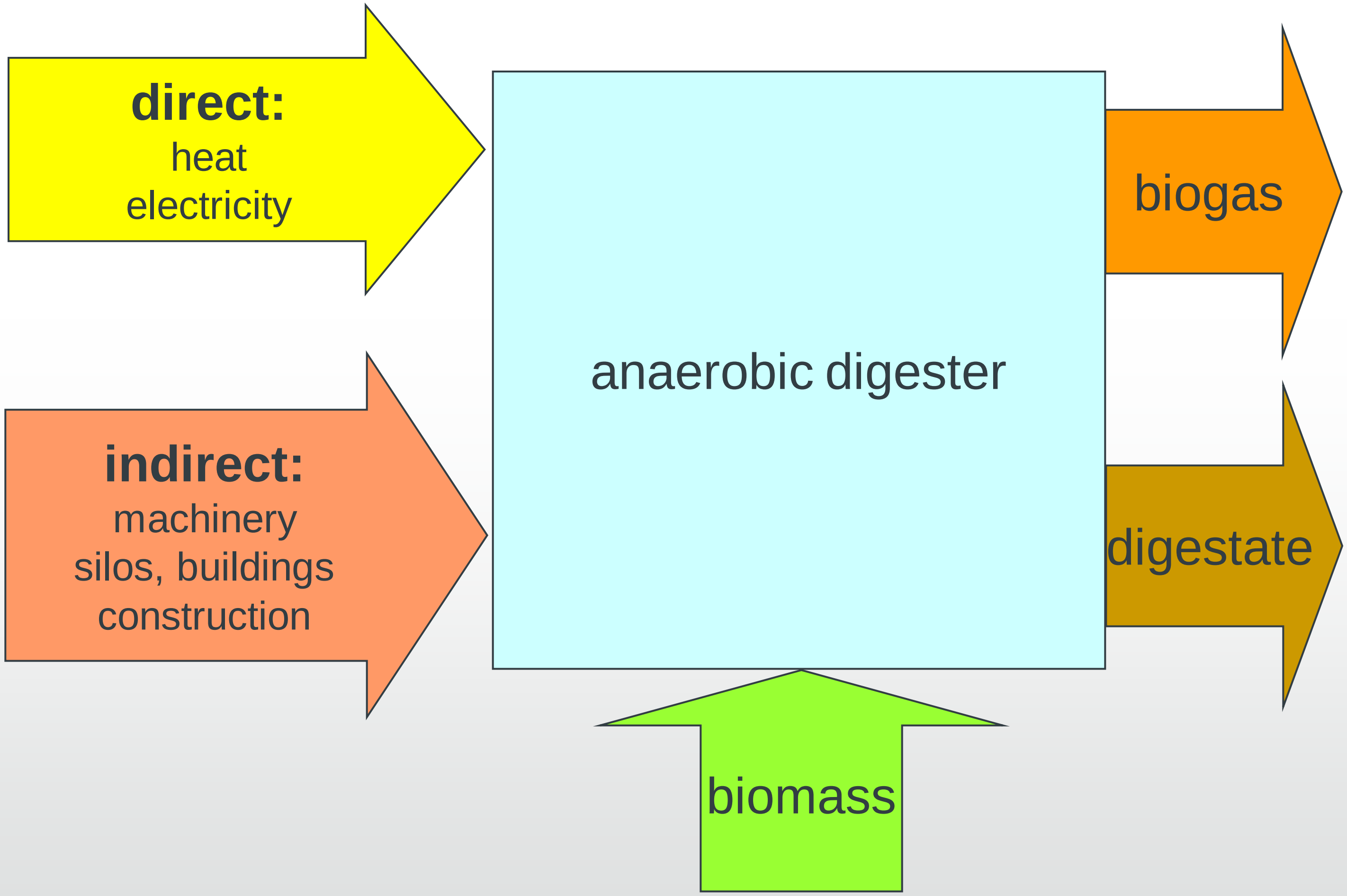
material	energy requirement (GJ/tonne)
concrete	4.9
construction steel	35
plastics	87
construction energy	3.4% total embodied energy

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

Plant construction

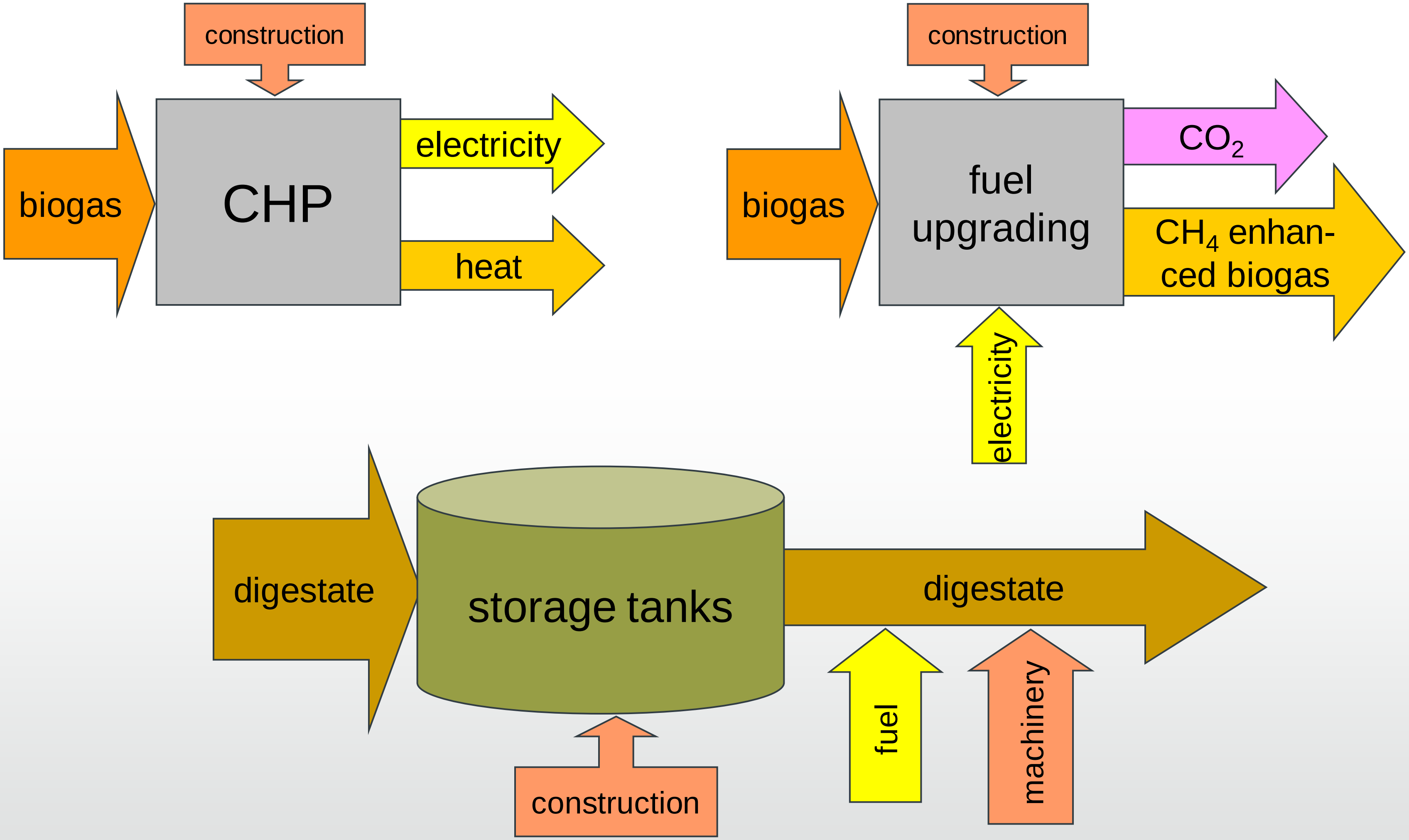
materials	tonnes	energy (GJ)
concrete	5000	24,500
bricks	36	35
wood	10	68
construction steel	90	3,150
asphalt	1000	3,236
embodied total		32,500
construction		1,105
total for plant		**33,605**

Anaerobic digester



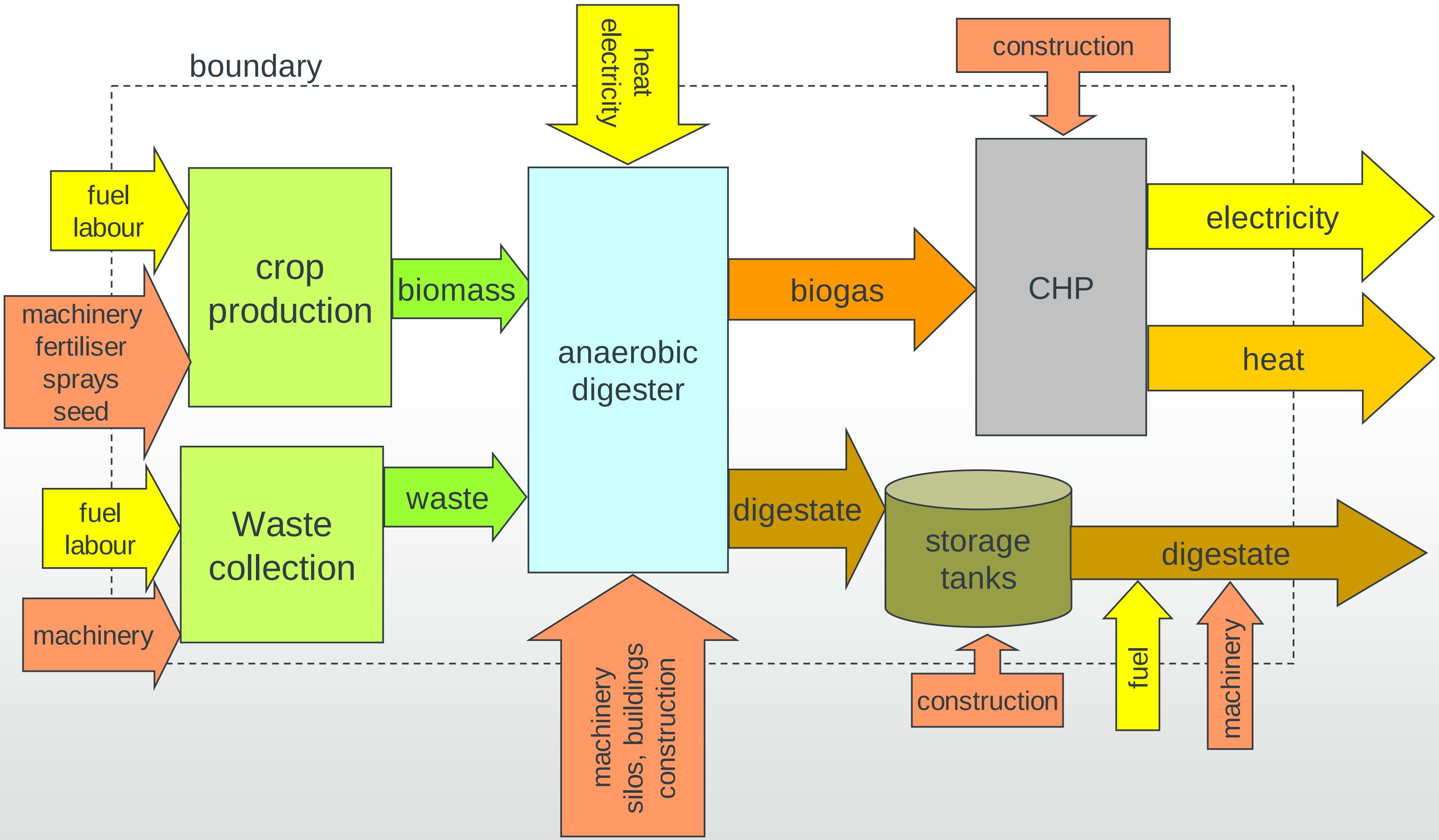

boundary
In
crop production
anaerobic digester
post treatments
Out

Post digestion

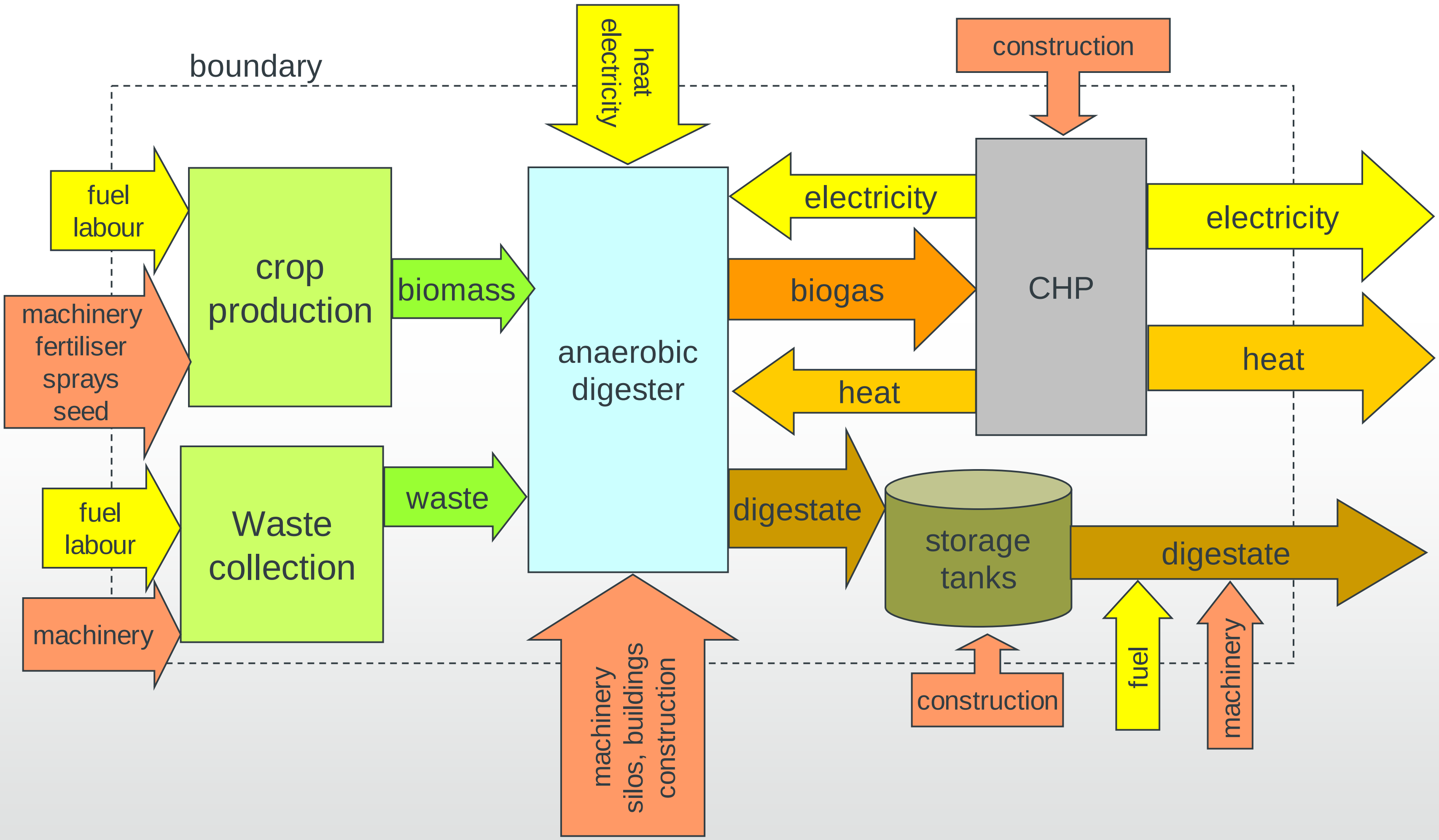


The complete system

The complete system



Self generated heat and electricity



An example for crop digestion

- Digester:

  capacity = 3800 m^3

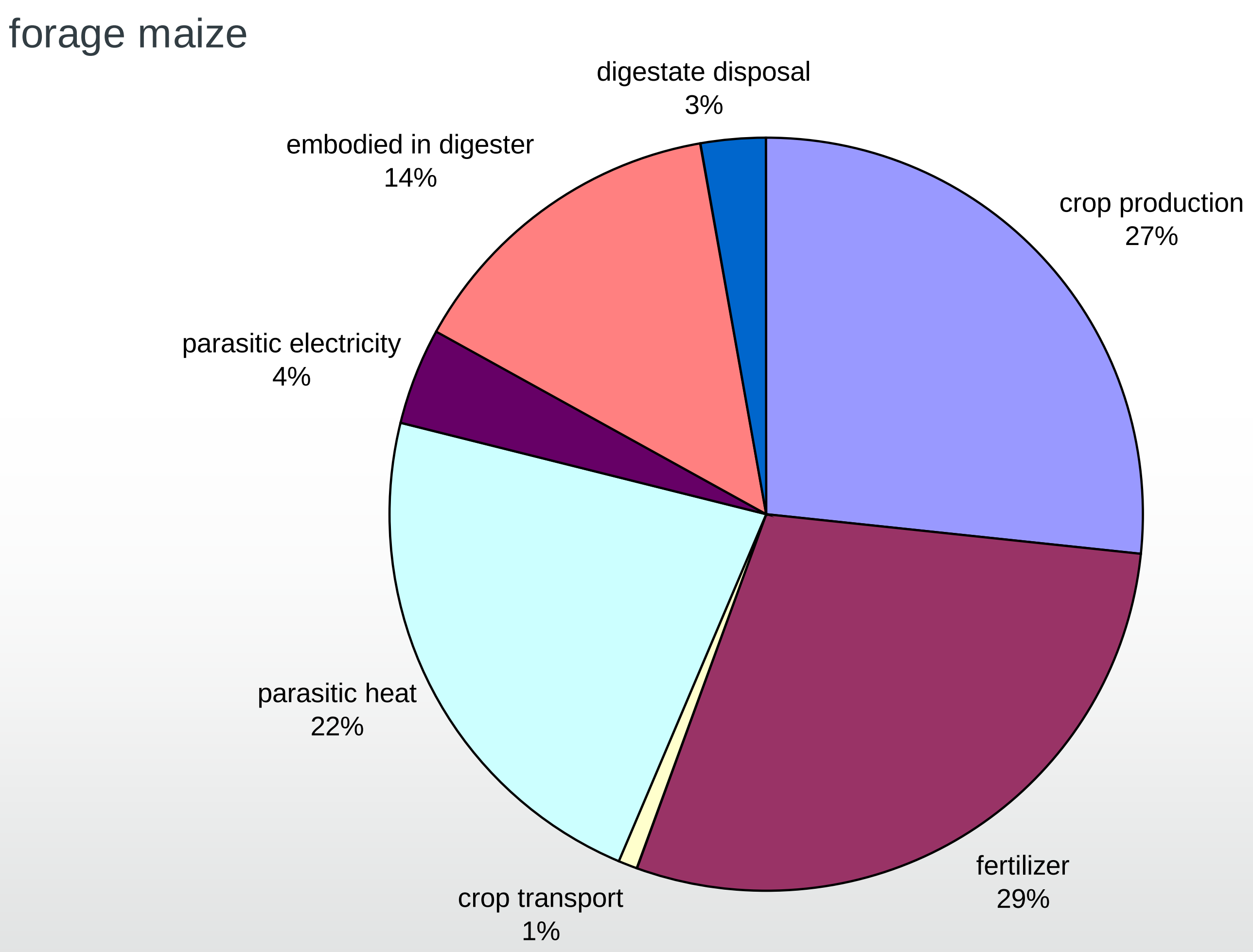
  construction = mainly concrete

- Life expectancy of digester = 20 years
- Feedstock = single substrate (maize)
- CHP = 30% electricity efficiency
- = 55% heat efficiency
- Climate = UK
- Fertiliser = mineral (fossil fuel based)

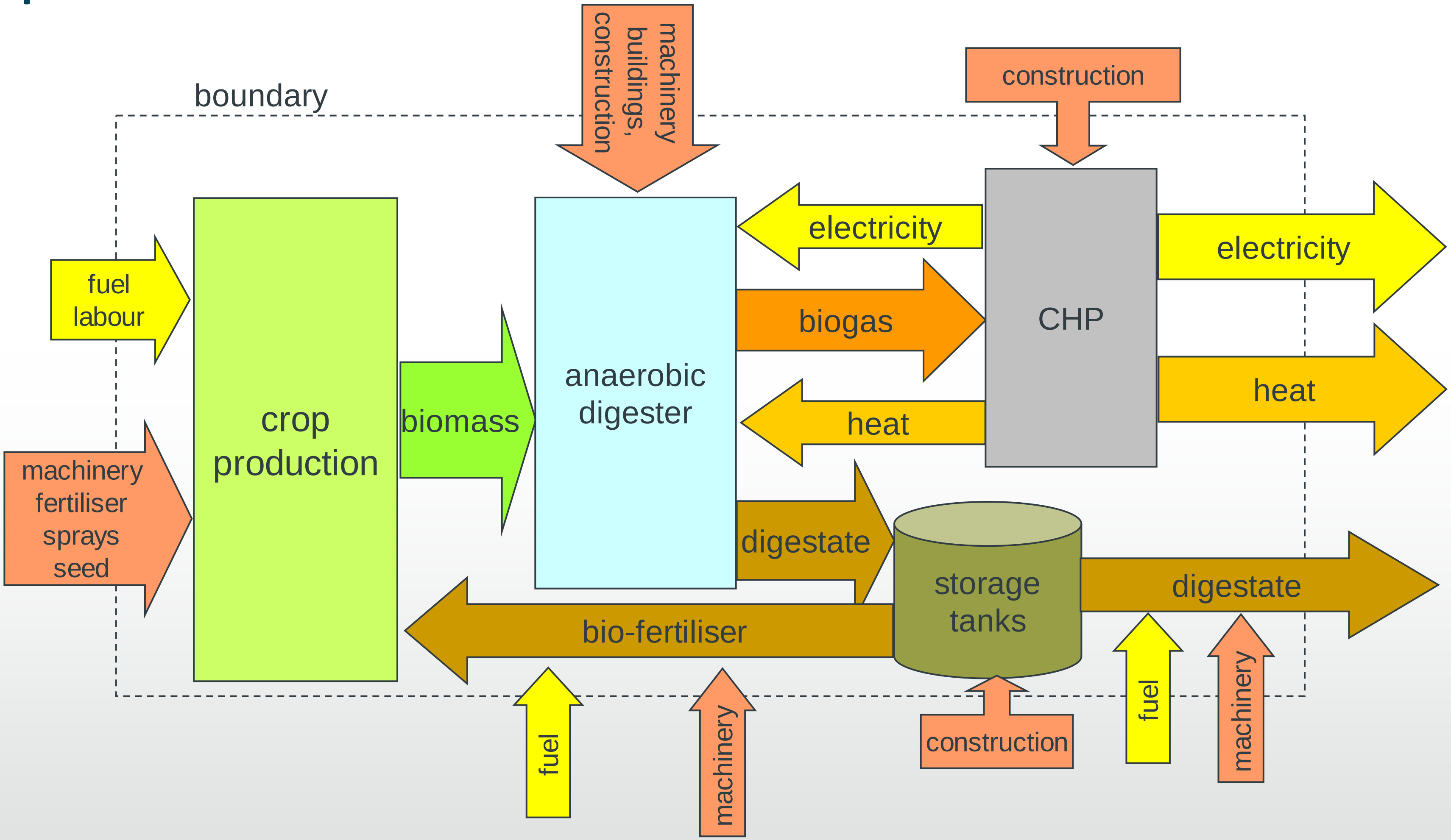
An example for crop digestion

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

Energy requirements



Recycling the digestate in crop production



Energy balance using digestate

crop production (direct & indirect)	4,231 (7,429)	GJ/yr
crop transport	274	GJ/yr
digester embodied energy	2,109	GJ/yr
digestate disposal	430	GJ/yr
energy into system	**7.5 (10.9)**	**TJ/yr**
methane produced	1.94	10^6 m^3
Electricity generated	20.8	TJ/yr
Heat generated	34.7	TJ/yr
parasitic electricity required	0.7	TJ/yr
parasitic heat required	4.1	TJ/yr
electrical energy out of system	20.1 (5597)	TJ/yr (MWh/yr)
heat energy out of system	30.6 (8501)	TJ/yr (MWh/yr)
Energy balance (E_{out} – E_{in})	**43.2 (39.9)**	**TJ/yr**

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 has an energy value of 21.4 MJ/m^3 or 5.95 kWh

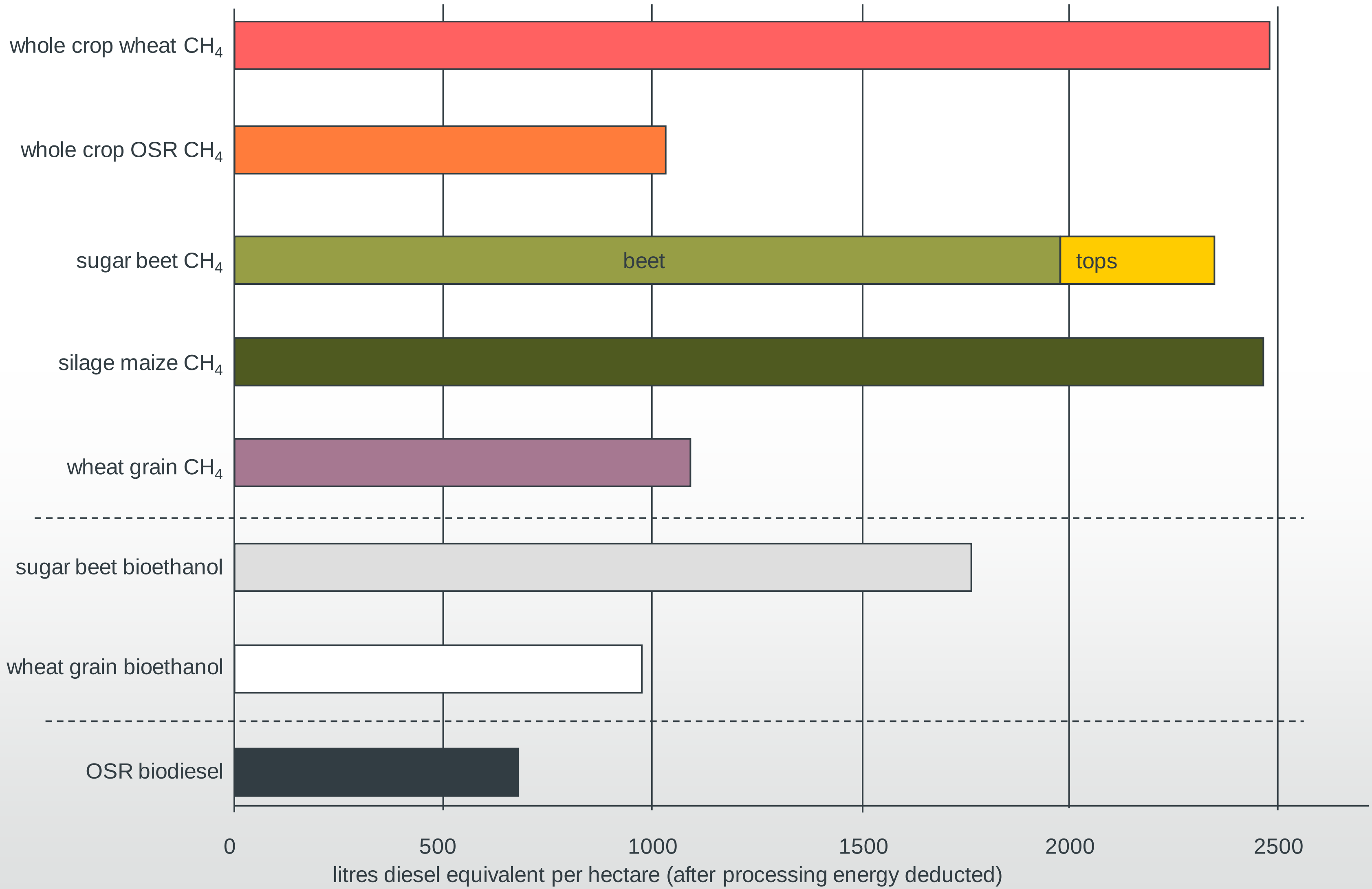
Biogas energy consumed in upgrading = 0.5 / 0.3 = 1.67 kWh/m^3

% of energy available consumed in upgrading = 1.67/5.95 = 28%

AD – energy balance

		CHP	vehicle fuel
crop production (direct & indirect)	GJ/year	1859	
parasitic electricity	GJ/year	393	3261
parasitic heat	GJ/year	3655	3655
digester embodied	GJ/year	109	109
total	**GJ/year**	**6174**	**9043**
energy in methane produced	GJ/year	38702	38702
generated electricty	GJ/year	13546	3261
generated heat	GJ/year	19351	4658
exported electicty	GJ/year	13153	
	MWh/year	3654	
exported heat	GJ/year	15696	
	MWh/year	4360	
energy in upgraded CH_4	GJ/year		29386
	l diesel/year		820831
energy balance (E_{out} - E_{in})	**GJ/year**	**22675**	**20343**

Production of vehicle fuel



Alternative feedstock

- Agricultural
  - Animal slurries and manures
  - Crop residues
  - Food waste
- Others
  - Verge cuttings
  - Communal grass areas
  - Glycerol & oilseed rape cake
  - Brewers grains

Food waste

- No energy required for production
  - Transport
  - Digestion
- Digestate replaces mineral fertilisers
- Energy saving of 2139 GJ/year
- CO_2 saving of 153tonnes

		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
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**

Conclusion

- To determine an energy balance
  - identify system boundaries
  - account for direct and indirect energy used
    - include energy to produce/transport the crop
    - energy to process the crop into fuel
- (If the energy balance is negative – it takes more energy to produce the fuel than is contained in the fuel!

(Try another crop or another fuel!)