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Task 1.1.3 Distributed Biogas Production

New Residential Area Circular Economy Concept

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Distributed Biogas Production in New Residential Area

In this task, the feasibility of distributed biogas production using circular economy concept in the new residential area is assessed.

First, various scenarios for biogas production and nutrient circulation in a new theoretical residential area were studied. The potential and characteristics of various resources for biogas production and nutrient circulation are presented. Then the options for infrastructure of feedstock collection and biogas production are analyzed. Finally the energy balance of the different options as well as the role of the digestate nutrients in local crop and greenhouse production is evaluated (Figure 1).

Secondly, the city planning process of new residential areas is analyzed. The drivers and barriers of new infrastructure and circular economy concept are discussed. Finally, recommendations to enable socio-technical transition are presented.

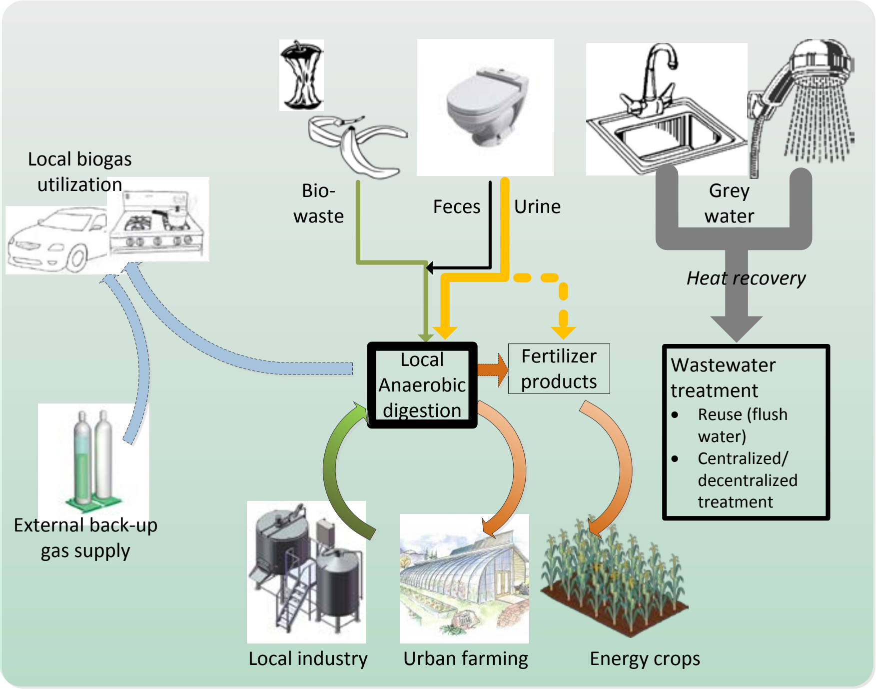


Figure 1: Distributed biogas production and resource recovery

Content

Resource Recovery via Distributed Biogas Production

- Resource Recovery Potentials

1. Introduction

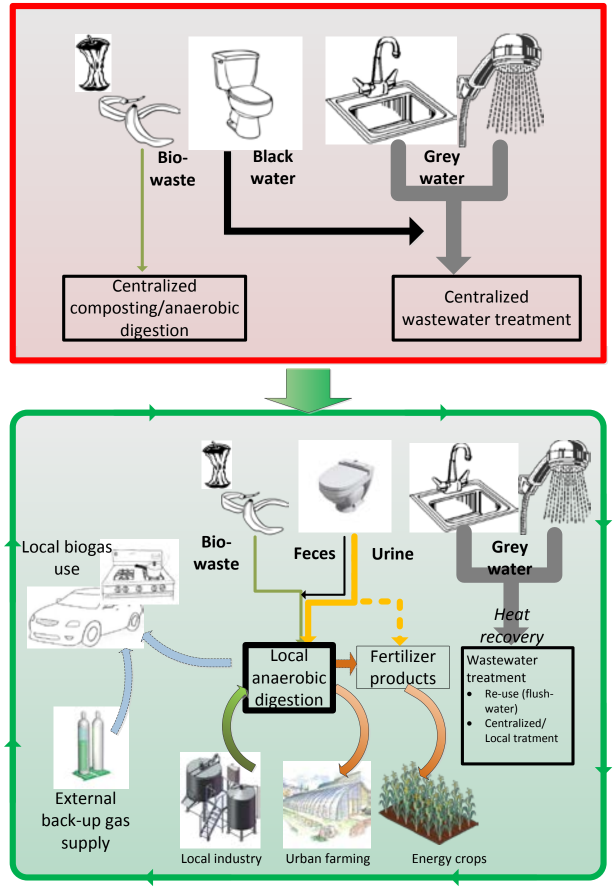


Figure 2: Conventional and resource recovery collection systems for household waste

Conventional sanitation used in Finland and in most Western countries is a linear system, where especially nutrient recycling is seriously limited. In a conventional wastewater-treatment plant (WWTP), energy and chemicals are used to remove nutrients from wastewater. In a WWTP, nitrogen (N) is often partly converted to atmospheric nitrogen, partly used by aerobic microorganisms for their growth in activated sludge processes, and partly remaining in treated water. Phosphorus (P) is usually precipitated into an insoluble form, limiting its reuse. Treated sewage sludges are currently landfilled, incinerated, composted, anaerobically digested (AD) (Manfredi & Pant, 2011), and/or recycled for agriculture (Eurostat, 2016). The activated sludge process used in most wastewater treatment plants also consumes considerable amounts of energy, although consumption can be partly covered through anaerobic digestion of excess sludge. To replace current linear nutrient flow with more closed cycles and energy-efficient treatment, a new sanitation system is needed.

Source-separating sanitation and decentralized treatment of domestic wastewater have been suggested as alternatives with the potential to improve nutrient recycling and energy efficiency in sanitation systems (Kujawa-Roeleveld & Zeeman, 2006; Tervahauta, 2014). Furthermore, decentralized systems have the potential to reduce infrastructure costs and support innovations that can be exported to emerging economies (Quezada et al., 2016). Distributed energy systems may increase renewable energy production capacity and energy self-sufficiency (Ruggiero et al., 2015), as well as enhance sustainability in terms of flexibility, locality, and networking (Alanne & Saari, 2006). To promote local resource cycles and renewable energy production, a decentralized circular system (Figure 2) that consists of source-separating low-water toilets, small-scale AD, and local utilization of nutrients and produced gas within a residential area was studied.

AD is an attractive waste treatment technology because it generates renewable energy and supports nutrient recycling. Furthermore, AD is suitable to urban areas because the process occurs in enclosed tanks, and emissions are easy to manage (Edwards et al., 2015). However, there are also several limitations related to AD technology and its establishment: the risk of harmful substances (e.g., heavy metals, organic pollutants), lack of acceptability (Aubain et al., 2002), unsupportive or unclear legal frameworks (Hukari et al., 2016), and governance aspects, such as poor source-separation of wastes or inefficient plant operation (Zabaleta & Rodic, 2015).

In this report, our objective is to calculate the technical potential of a decentralized circular system for a residential area of about 10,000 people. Furthermore, the aim is to find out the preconditions for the implementation of the system. The opinions on the system were solicited in semi-structured interviews with 17 water-, waste-, gas-, energy-, and urban land-use planning experts, and in a workshop with seven experts. In directed content analysis (Hsieh & Shannon, 2005), drivers, barriers, and enablers were specified (Quezada et al., 2016).

2. Resource Recovery Potential of Household Waste

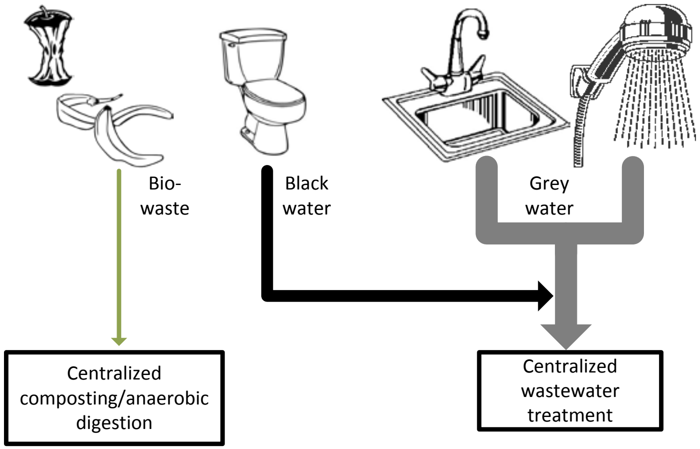


Figure 3: Conventional collection of household waste

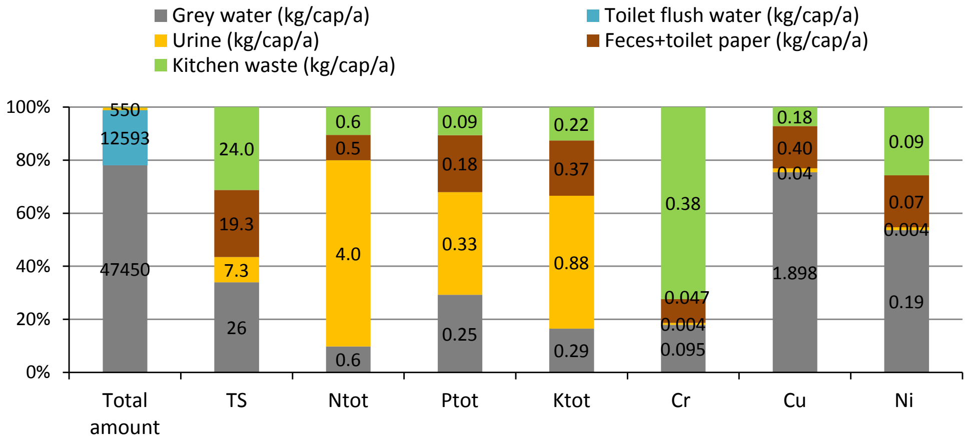


Figure 4: The share of volumes, nutrients, and heavy metals in household waste streams

Organic waste streams from urban households

In conventional sanitation and waste treatment, organic wastes from households in urban areas are divided into source-separated bio-waste and wastewater. Wastewater includes combined black water (urine, faeces, flush water) from toilets (21% of volume) and grey water from washing and showering (78% of volume) (Figure 3).

Grey water forms about 78% of total waste streams and toilet flush water about 21%, with the organic fraction (and toilet paper) about 1% of total household waste streams. However, when considering total solids, despite large volumes of grey water, it contains only 35% of solids (Figure 4).

In addition to low concentration of solids, the nutrient content of grey water is relatively low, with only 10, 29, and 16% of total household waste stream for nitrogen, phosphorus, and potassium, respectively. Instead, grey water includes a major share of heavy metals (e.g., 75% Cu and 54% Ni).

Because of low organic matter content and high heavy metal concentrations, it is necessary to separate grey water from the waste stream when aiming for local distributed resource recovery. The reuse of grey water as flush water and heat recovery options could be sought, as well as local treatment options, but they are excluded from this study.

Resource Recovery Potential of Household Waste

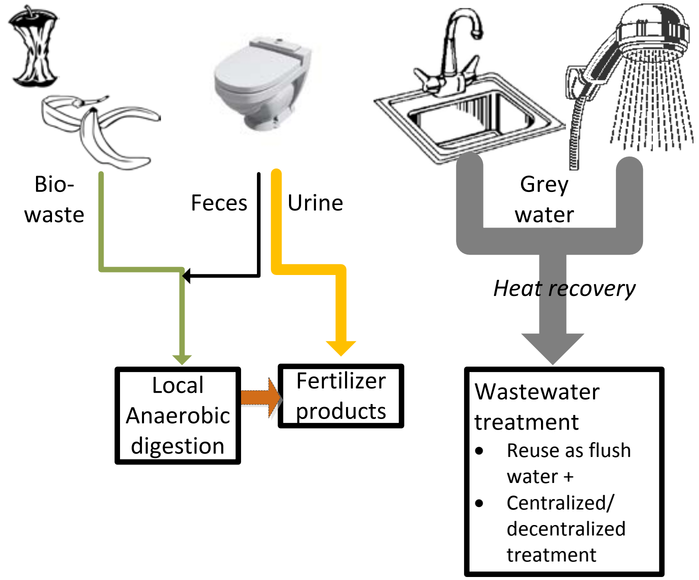


Figure 5: Local resource recovery concept; for urine, separation and collection together with faeces is considered

Nutrients

When grey water is separated from the household waste stream (Figure 5), urine contains about 80% of the total wet weight (and volume) when flush water is not included. Urine also contains most of the nutrients; nearly 80% of nitrogen, 55% of phosphorus, and 60% of potassium (Figure 6). Faeces is the second important nutrient source for phosphorus and potassium, while about the same amount of nitrogen is found both in faeces and other bio-waste.

Energy

Although kitchen waste forms only 10% of total waste wet weight, it has the highest energy potential (~70%) due the good degradability and high methane production potential. The remaining 30% of the energy potential comes from faeces, as the methane production from urine is assumed to be negligible. Because of the high nutrient content, low energy potential, and high volume, separation of urine from the waste stream would be beneficial (Figure 6).

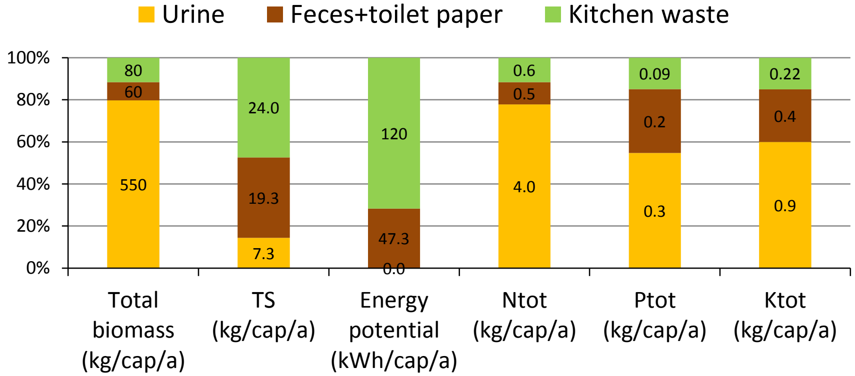


Figure 6: The share of total weight, energy potential (as methane), and nutrients in household waste streams when gray water is excluded

Potential & Value of Household Waste

Table 1: Theoretical maximum methane and nutrient recovery from household waste (no plant biomass) for 10,000 people

	Faeces	Urine	Kitchen Waste	**Total**
Methane production m^3/a	47331	0	119848	**167179**
Primary energy production MWh/a	473	0	1198	**1671**
N recovery (t/a)	5	40	6	**52**
P recovery (t/a)	2	3	1	**6**
K recovery (t/a)	4	9	2	**15**

Table 2: Theoretical maximum resource value from waste for 10,000 people

	Faeces	Urine	Kitchen Waste	Total
Methane production (€/a)	47710	0	120807	168517
N tot recovery (€/a)	6023	44165	6592	56779
P tot recovery (€/a)	3285	5913	1618	10816
K tot recovery (€/a)	7300	17520	4410	29230
Total (t€/a)	**64**	**68**	**133**	**265**

Methane 1.4 €/kg (0.72 kg/m^3, Gasum price), N-mineral fertilizer 1.1 €/kg (Sitra 2015), P-value 1.8 €/kg (Sitra 2015), K-mineral fertilizer 2.0 €/kg (Virkajärvi, 2012)

Table 3: Indirect energy savings and monetary consumer savings due to decreased water purification/use and wastewater treatment

	Energy savings (kWh/a)	Consumer value (€)
Per/cap/a		
Water purification	7.7	20.5
Wastewater treatment	3.6	24.8
Total	**11.3**	**45.3**
10,000 residents/a	MWh/a	(t€)
Water purification	77	205
Wastewater treatment	36	248
Total	**113**	**453**

Nutrient recovery potential

The annual nutrient recovery potential from household wastes is 52, 6, and 15 tons of nitrogen, phosphorus, and potassium per 10,000 residents. The value of these nutrients would be about €275,000/a. The highest nutrient recovery potential is for nitrogen from urine; 40 t/a, having a value of €57,000/a (Tables 1 and 2). When calculated for the urban population in Finland (70% of the population), P recovery potential from toilet waste and bio-waste is 4258 t/a, corresponding to 13% of fertilizer phosphorus use (33,400 t/a, MMM, 2011). For nitrogen, the recovery potential for the Finnish urban population, 19,768 t/a, corresponds to 9% of fertilizer nitrogen use (230,700 t/a, MMM, 2011).

Energy recovery potential

The primary energy production potential from household wastes via AD is about 1.7 GWh/a per 10,000 residents (Table 2). For Finland, the energy recovery potential via AD of household bio-waste and faeces would be 640 GWh/a when calculated for the urban population (70% of the total population).

Indirect potential

In addition to the direct potential of resource recovery in the form of nutrients and energy, the concept may also provide significant indirect benefits. If flush water use could be completely avoided and/or grey water used instead, 125,000 m^3/a purified water would be saved per 10,000 residents, and the same volume would be avoided by wastewater treatment plants. This could mean energy savings in wastewater treatment and clean water manufacturing of about 113 MWh/a. As well, chemical consumption in waste water treatment would be reduced.

For residents, savings of €45/cap/a could be achieved in water bills (Table 3). Indirect savings may even exceed the value of resource recovery (the value of nutrients and methane). However the fact that the cost and energy requirements of new sanitation systems (e.g., vacuum toilets) is difficult to estimate and costs may even exceed those of conventional sanitation must be addressed.

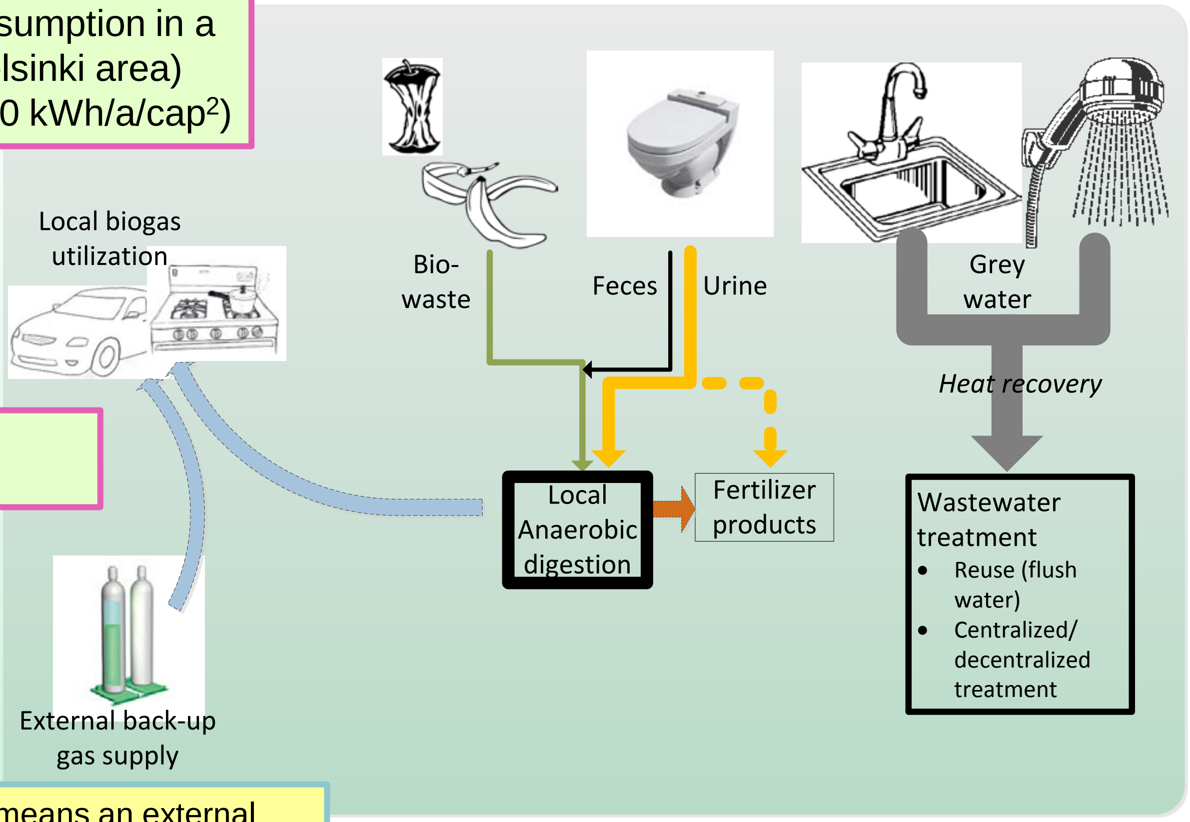
Primary Energy Potential of Household Waste per 10,000 Inhabitants

1.7 GWh/a (167 kWh/a/cap)

- 2% of average heat and electricity consumption in a residential area (8,500 kWh/a/cap[1], Helsinki area)
- 0.7% of all energy consumption (23,400 kWh/a/cap[2])

For 2,772,000 km driving
~140 gas vehicles
(4.3 kg/100 km–20,000 km/a/vehicle)

Or gas for 9,900 gas stoves
(Estimated consumption 1 kg/month/gas cooker)



In vehicle use, local production of **4.2% of need** means an external supply is required
(Assumed 0.33 vehicles/cap (Helsinki, 2014) → 3,300 vehicles)[3]

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[1] Average heat+energy consumption per capita in 2008, calculated from six residential area in Helsinki (Arabianranta, Jakomäki, Länsi-Herttoniemi, Länsi-Pakila, Myllypuro, Takatöölö) Helsingin ympäristötilastot.

[2] Average energy consumption per capita in the Helsinki area, including transportation. Helsingin ympäristötilastot.

[3] Helsingin kaupunki, liikenteen kehitys Helsingissä 2015.

3. Enhancing Methane Production Using Plant Biomass

Figure 7: A scenery field in Tampere

Table 4: The areas and costs of scenery fields and meadows (Class B) per residents in the biggest cities in Finland (2009)

	Area ha	Area (ha/cap)	Cost (€/cap)
Tampere (2013)	160	0.0007	0.5
Helsinki	900	0.0015	1.8
Espoo	320	0.0013	0.8
Vantaa	360	0.0018	1.6
Turku	460	0.0026	0.5
Range	**160–460**	**0.0007–0.0026**	**0.5–1.8**

Urban fields and meadow areas

The potential of energy crops grown in scenery fields and meadows as a an extra raw material for AD was studied. Scenery fields and meadows (Figure 7), are maintained by the city, using agricultural methods that already exist in the biggest cities in Finland. The benefit of these areas is that they offer lively variation to urban landscapes with lower costs compared to more regularly maintained green spaces (parks) (Söyrinki, 2012). The area of scenery fields in urban areas varies between cities (Table 4). In Tampere, the area per resident was the lowest, at 6 m^2/cap, and the highest was in Turku, at 26 m^2/cap. Town planning has a major impact on the scenery field areas, and as this study is done mainly for new residential areas, the highest existing scenery field area (26 m^2/cap) was used as a design value. The cost of scenery fields varies between €0.5 and €1.8/cap (Tampereen Kaupunki, 2016) (Table 4).

Several plant species could be grown for biogas production, but in this study, grass and energy maize (not the same species as edible maize) were used as an example. Grass presents a modest yield example, and was selected because, at present, some scenery fields are already sown with grass and clover, a suitable substrate for biogas production (Seppälä, 2013). The maize was used as a high-yield example, as in Germany, energy maize is the most used high-yield energy crop for biogas production, and it could also be grown in Finland (Seppälä, 2013). When grown in scenery fields, the plant production would not compete with food production.

Biogas Energy Potential

Household Waste + 26 m²/cap Urban Field and Meadow Areas with Grass or Maize (26 ha – 10,000 residents)

Energy recovery potential

If 26 m²/cap urban fields and meadow areas are used to grow grass for biogas production, the total energy production potential of the distributed biogas system is increased by 45% (from 167 to 243 kWh/cap). If maize is used, the energy potential could be increased by 97% to 330 kWh/cap (Figures 8 and 9). Plant biomass forms 34% (grass)–46% (maize) of solids and 8–17% of nutrients.

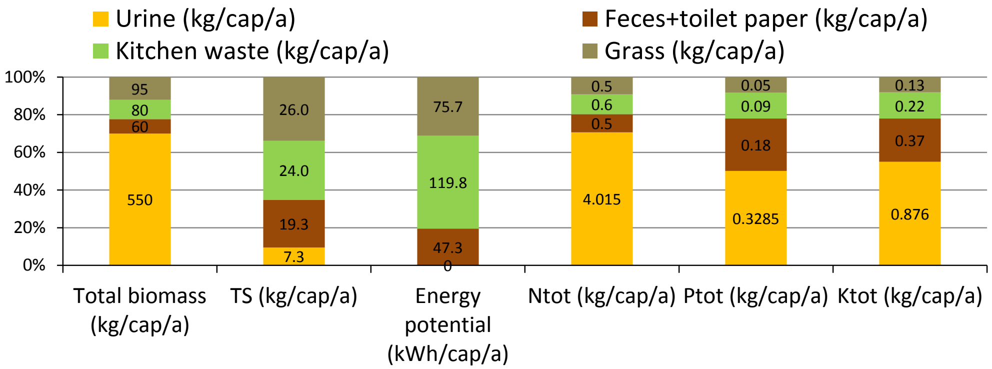


Figure 8: The share of total weight, energy potential (as methane), and nutrients between household waste streams and grass biomass

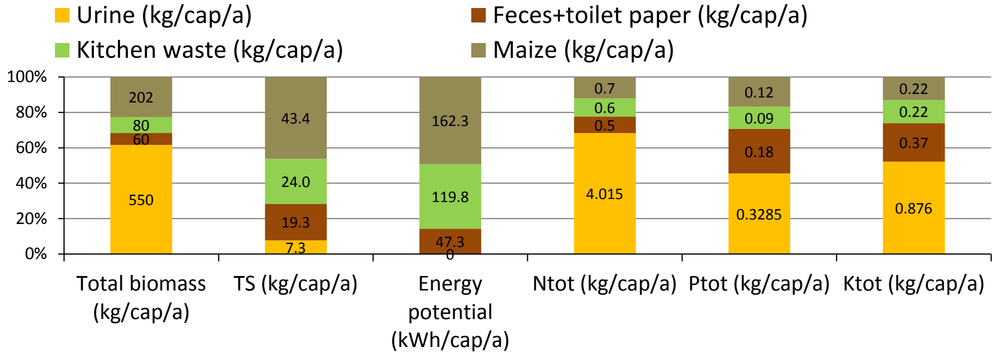


Figure 9: The share of total weight, energy potential (as methane), and nutrients between household waste streams and maize biomass

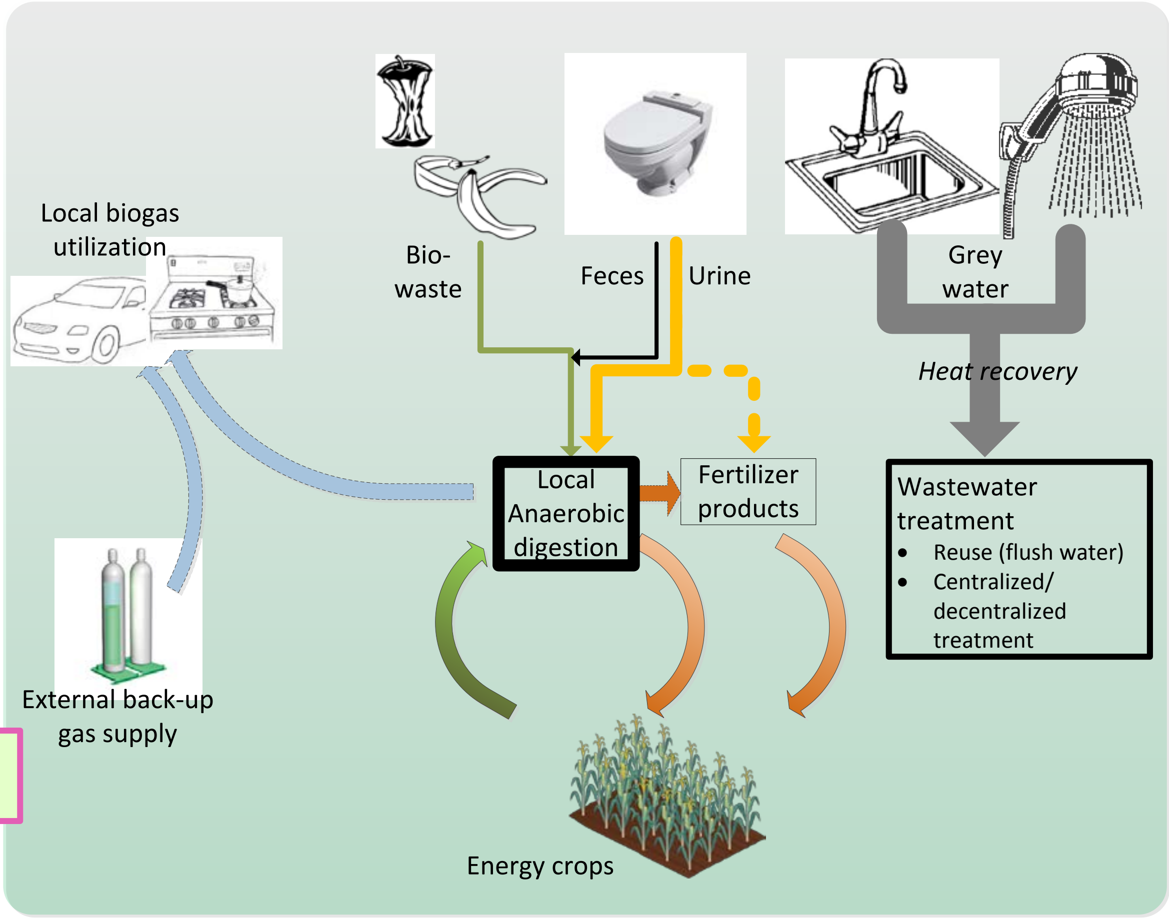
Primary Energy Potential of Household Waste per 10,000-Inhabitant Residential Areas + 26 ha Areas for Grass or Maize

2.4 GWh/a (grass)–3.3 GWh/a (maize)
243 kWh/cap/a–330 kWh/cap/a

- 2.9–3.9% of average heat and electricity consumption in a residential area (8,500 kWh/a/cap, Helsinki area)[1]
- 1–1.4% of all energy consumption (23,400 kWh/a/cap)[2]

For 4,027,000–5,464,000 km driving
Gas for 200/270 gas vehicles
(4.3 kg/100 km–20,000 km/a/vehicle)

Or gas for 14,000/19,000 gas stoves
(Estimated consumption 1 kg/month/gas cooker)



In vehicle use, local biomethane production of 6/8% of need, an external supply required (assumed 0.33 vehicles/cap (Helsinki) → 3300 vehicles)[3]

Sustainable Bioenergy Solutions for Tomorrow

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[1] Average heat+energy consumption per capita in 2008, calculated from six residential area in Helsinki (Arabianranta, Jakomäki, Länsi-Herttoniemi, Länsi-Pakila, Myllypuro, Takatöölö) Helsingin ympäristötilastot.

[2] Average energy consumption per capita in the Helsinki area, including transportation. Helsingin ympäristötilastot.

[3] Helsingin kaupunki 2016, liikenteen kehitys Helsingissä 2015.

4. Other Local Biomass Sources (a Greenhouse and a Brewery)

Figure 10: Greenhouse cultivation of tomato and cucumber

Table 5: Production of tomato, cucumber, and plant residues in greenhouse cultivation (values from expert audition)

	Production (t/a)	Residues (kg/a)
3000 m^2 (1500 m^2 +1500 m^2)		
Tomato	100	24
Cucumber	168	46
5000 m^2 (2500 m^2 +2500 m^2)		
Tomato	168	40
Cucumber	280	77

Table 6: Average consumption of tomato and cucumber in Finland (Luke, 2016; Kasvitase, 2005)

Average consumption	(kg/cap/a)	(t/10 000 ppl)
Tomato	11	110
Cucumber	8	80

Greenhouse cultivation

To recycle nutrients from the new resource recovery system, local, large-scale greenhouse cultivation of tomato and cucumber was studied (Figure 10). Greenhouse size was determined to be 3,000 m^2, which is currently a typical greenhouse area in Finnish companies (Kauppapuutarhaliitto, 2016). Half of the area was considered to be for cucumber cultivation and half for tomato cultivation.

Although the consumption of greenhouse goods was not limited to residential areas, the 3,000 m^2 would approximately cover the tomato and cucumber production for 10,000 people (Tables 5 and 6).

The plant residues from greenhouse cultivation were considered to be used for biogas production (Table 5).

Other Local Biomass Sources (a Greenhouse and a Brewery)

Figure 11: A micro-brewery

Table 7: Brewery by-products

Brewery	Beverage production (L/a)	By-products (t/a) (ww)
Pyynikki brewery	500,000	167
Rekola brewery	150,000	50
Sonnisaari brewery	100,000	33
Stadi brewery	100,000	33

Industrial biomass sources

Various industrial activities may exist or can be planned for residential areas. Many industrial processes produce by-products or waste suitable for biogas production. Examples of such industries could include bakeries and small-scale breweries, the number of the latter increasing rapidly in Finland during the last decade. The possibility to treat waste locally for energy production on site could also attract operations in the area. This could be taken into consideration in the city planning phase.

Small-scale craft beer brewery

In this study, a small-scale craft beer brewery (Figure 11) was used as an example of a biodegradable waste-producing industry that could be located in a residential area. Small-scale breweries produce typically 100,000–500,000 L annually (Table 7), and formed organic by-products are about one third of the production (expert audition).

In this study, a small-scale brewery with production of 500,000 L, equal to the Pyynikki brewery in Tampere, Finland, was chosen. The by-products formed at the brewery were used by a local AD plant.

Primary Energy Potential of Household Waste in 10,000-Inhabitant Residential Areas + 26 ha Areas for Grass or Maize + 3,000m² Greenhouse Residues + Brewery Residues

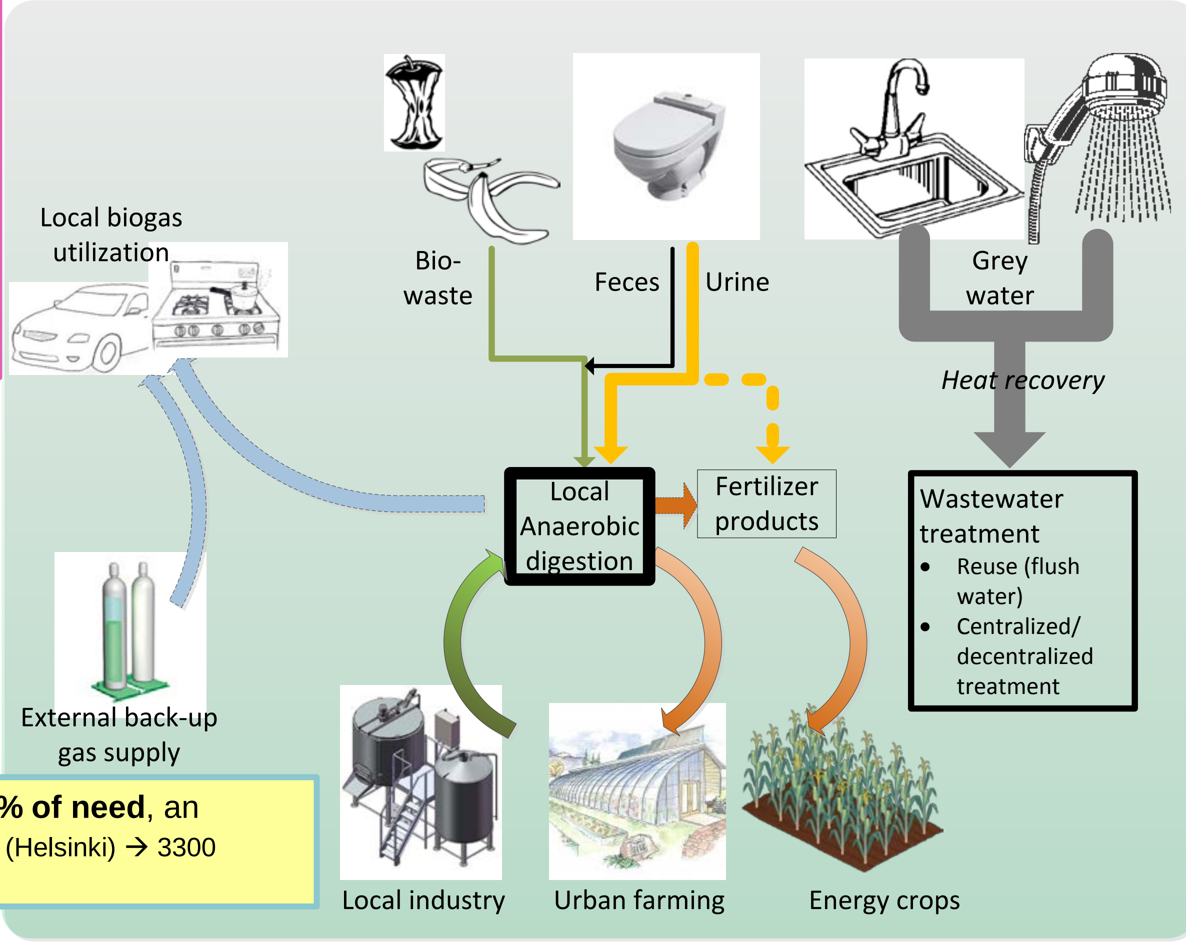
2.6 GWh/a (grass)–3.5 GWh/a (maize)

- 3.1– 4.1% of average heat and electricity consumption in a residential area (8,500 kWh/a/cap[1], Helsinki area)
- 1.1–1.5% of all energy consumption (23,300kWh/a/cap[2])

For 4,343,000–5,789,000 km driving
Gas for 217/289 gas vehicles
(4.3 kg/100km–20,000 km/a/vehicle)

Gas for 15,000/21,000 gas stoves
(Estimated consumption 1kg/month/gas cooker)

In vehicle use, local biomethane production of **7–9% of need**, an external supply is required (Assumed 0.33 vehicles/cap (Helsinki) → 3300 vehicles).



Local biogas utilization

Bio-waste

Feces

Urine

Grey water

Heat recovery

Local Anaerobic digestion

Fertilizer products

Wastewater treatment
- Reuse (flush water)
- Centralized/ decentralized treatment

External back-up gas supply

Local industry

Urban farming

Energy crops

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[1] Average heat+energy consumption per capita in 2008, calculated from six residential area in Helsinki (Arabianranta, Jakomäki, Länsi-Herttoniemi, Länsi-Pakila, Myllypuro, Takatöölö) Helsingin ympäristötilastot.
[2] Average energy consumption per capita in the Helsinki area, including transportation. Helsingin ympäristötilastot.
[3] Helsingin kaupunki 2016, liikenteen kehitys Helsingissä 2015.

Primary Energy Potential of Household Waste in 10,000-Resident Example Area + 26 ha Area for Grass + 3,000 m² Greenhouse Residues + Brewery Residues

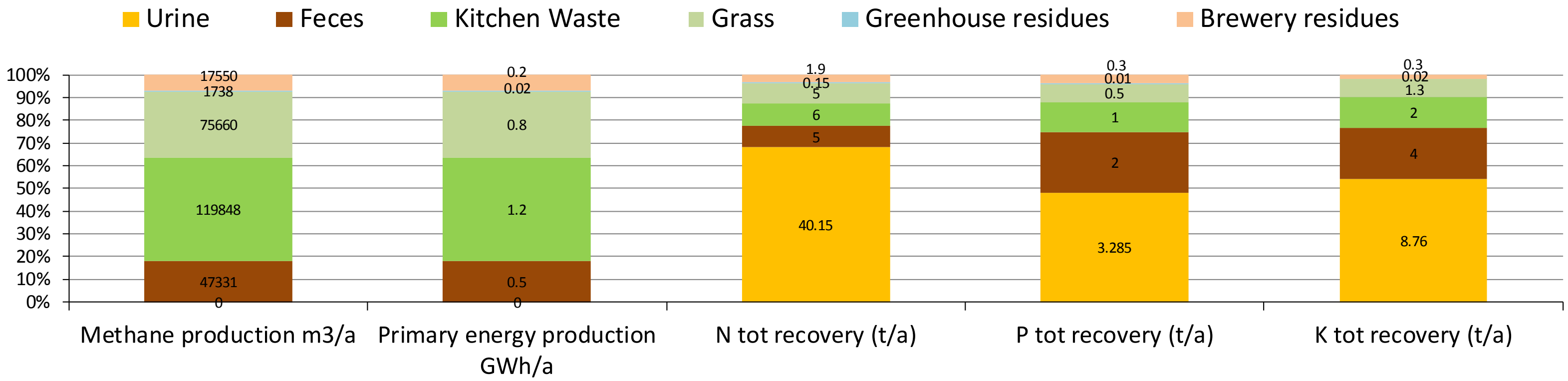


Figure 12: The share of methane production potential and nutrients in household waste streams, plant biomass (grass as an example), greenhouse residues, and brewery residues

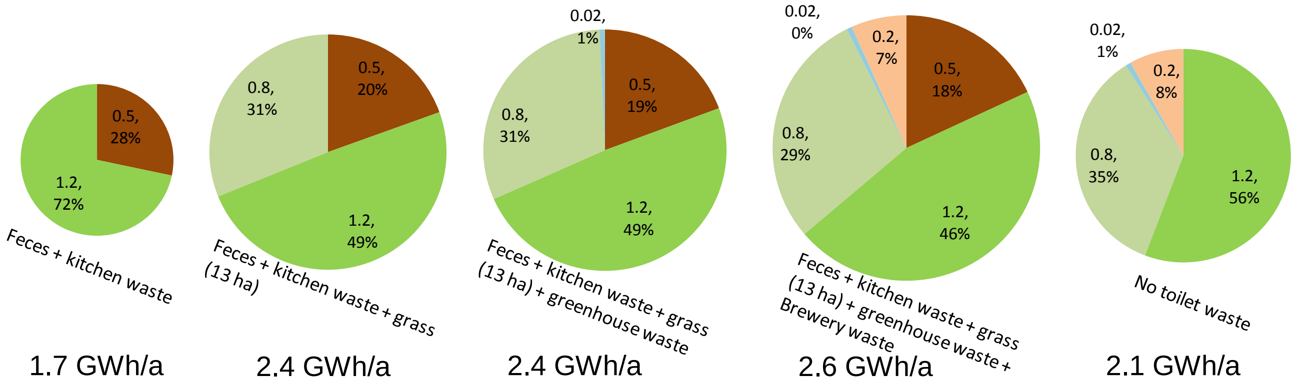
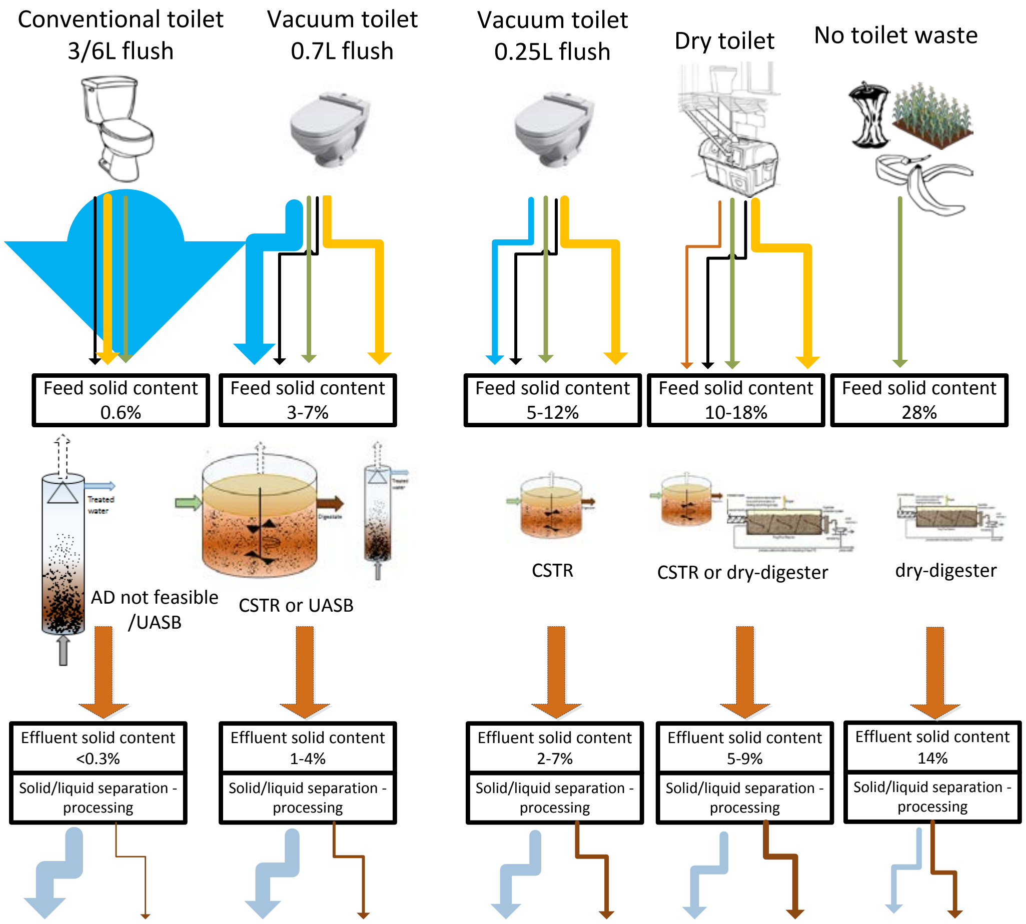


Figure 13: The share of primary energy production potential with different combinations of biomass directed to a local AD plant

5. Toilet Waste Collection and Biogas Production Technology



Conventional toilet 3/6L flush

Feed solid content 0.6%

AD not feasible /UASB

Effluent solid content <0.3%

Solid/liquid separation - processing

Vacuum toilet 0.7L flush

Feed solid content 3-7%

CSTR or UASB

Effluent solid content 1-4%

Solid/liquid separation - processing

Vacuum toilet 0.25L flush

Feed solid content 5-12%

CSTR

Effluent solid content 2-7%

Solid/liquid separation - processing

Dry toilet

Feed solid content 10-18%

CSTR or dry-digester

Effluent solid content 5-9%

Solid/liquid separation - processing

No toilet waste

Feed solid content 28%

dry-digester

Effluent solid content 14%

Solid/liquid separation - processing

Figure 14: The impact of a toilet waste collection system (flush volume and urine separation) on biogas reactor feed and digestate solid content when all feeds are considered; the higher solid content is achieved with 75% urine separation, and the lower when urine is not separated from black water

Source-separating toilet waste collection system

Collection and transportation technologies for toilet waste, reducing flush water volume drastically and allowing the separation of urine, are the key issues of the new sanitation concept and resource recovery–currently, no cost-efficient full-scale solutions exist. In this study, a vacuum toilet with different flush water volumes and a dry toilet with litter addition were studied. The vacuum toilet with 0.7 L flush volume is existing technology, e.g., in cruise ships (expert audition), while 0.25 L flush volume is an optimistic estimation, not currently in use. When the flushing water volume is reduced, the functioning of piping and pumping are other technical aspects that must be solved.

The flush water volume has the highest impact on the collected waste characteristics (e.g., solids concentration), followed by the possible urine separation (Figure 14). The volume of flushing water and whether urine is separated or not determine the type and size of needed anaerobic reactors. Upflow anaerobic sludge bed (UASB) reactors are usually used for dilute substrates and wastewaters, but De Graaf et al. (2010) applied it to a vacuum toilet (1.0 L/flush) and collected black water with a hydraulic retention time (HRT) of 9 d. However, UASB-type reactors are limited to low solid concentration (e.g., TS 2%) feeds, and with higher-concentration completely stirred tank reactors (CSTR), typically (TS 5–12%) or dry digesters (TS >15%) are used.

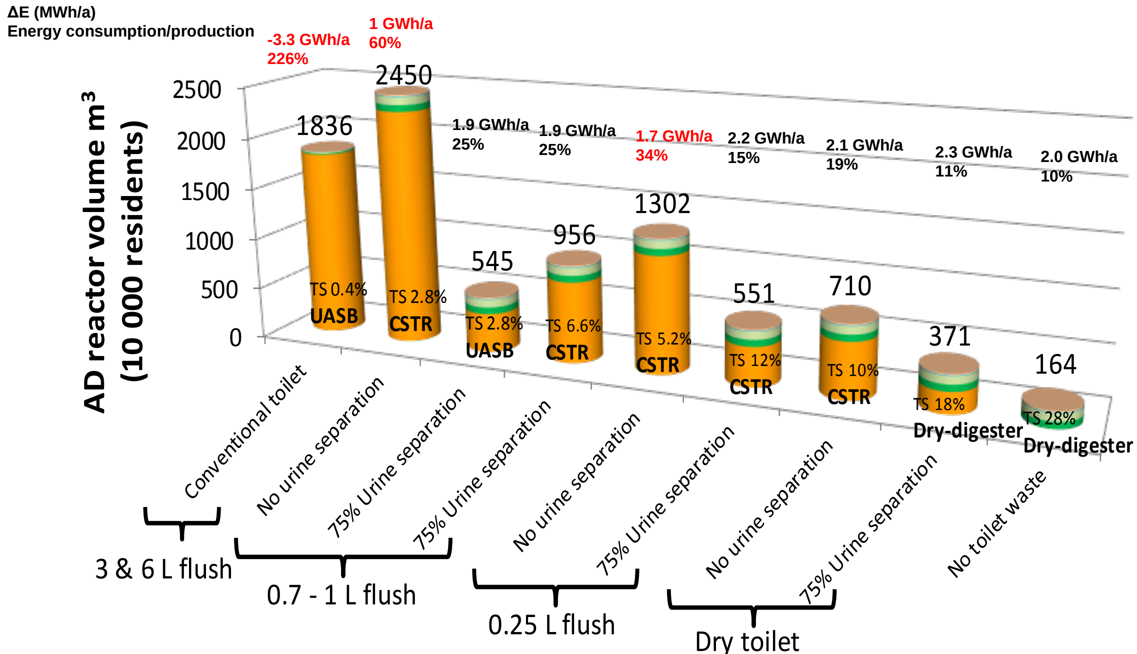
Required AD Reactor Volume for 10,000 Residents

AD reactor

The type and size of biogas reactor mostly depend on the volume of toilet flush water and whether urine is separated out. More water, higher is the treated volume and lower its concentration (Figure 15).

When reactor size and waste volume increase, AD plant energy requirements also increase, as the biogas reactor requires heating (here, hygienization at 70 ºC and digestion at 35 ºC is used) and mixing. For conventional toilets, the feed solid concentration is only 0.6% of the needed reactor volume (UASB) of 1,836 m^3. Heating the reactor and influent would require much more energy than is produced. If a vacuum toilet with a flush volume of 0.7 L is used without source separation, the solid concentration would be about 2.8% and reactor volume 2,450 m^3 if CSTR is used. However, a feed having about 2.8% solid content could be suitable for a UASB reactor (further studies needed), and this would reduce the reactor size to 545 m3 (54.5 m^3/cap).

About the same reactor size (551 m^3, 55.1 m^3/cap in CSTR) is needed for a vacuum toilet system having 0.25 L flush volume and urine source separation. The smallest reactors (371–710 m3) and lowest parasitic energy demands (11–19% of produced energy in form of methane) are for dry toilet systems.



	Conventional toilet	No urine separation	75% Urine separation	75% Urine separation	No urine separation	75% Urine separation	No urine separation	75% Urine separation	No toilet waste
🟧 Brewery residues	2	14	14	14	14	14	14	14	14
🟦 Greenhouse residues	1	6	6	6	6	6	6	6	6
🟩 Grass	13	78	78	78	78	78	78	78	78
🟩 Kitchen waste	11	66	66	66	66	66	66	66	66
🟧 Toilet waste	1809	2286	381	792	1139	387	546	207	0

Figure 15: The required volume of biogas reactor, including hygienization at 70 ºC for 10,000 residents and for each substrate;[1] energy ΔE shows the energy production (in methane) after decreasing energy consumed to run the mesophilic (35 ºC) AD plant; the percentage describes the share of energy consumed by production

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[1] Calculated using HRT of 5 d for UASB reactor and 30 d for CSTR and dry-digester, 20% head space added to reactor working volume. Average ambient (and substrate) temperature +4 ºC, Hygienization temperature 70 ºC, 85% heat recovery from hygienization step.

6. Energy Balance Estimation

Table 8: Energy balance estimation; transportation of brewery waste and greenhouse residues not included

	Vacuum toilet (0.7 L) 75% urine separation, UASB reactor[1]		Vacuum toilet (0.7 L) 75% urine separation, CSTR reactor		Vacuum toilet (0.25 L), 75% urine separation, CSTR reactor		Dry toilet, no urine separation, CSTR reactor		Dry toilet, 75% urine separation, dry digester		No toilet waste, dry digester	
	kWh/cap	GWh/ 10000 cap	kWh/cap	GWh/ 10000 cap	kWh/cap	GWh/ 10000 cap	kWh/cap	GWh/ 10000 cap	kWh/cap	GWh/ 10000 cap	kWh/cap	GWh/ 10000 cap
$E_{\text{Methane production}}$	262	2.621	262	2.621	262	2.621	262	2.621	262	2.621	215	2.148
$E_{\text{AD plant consumption}}$	-81	-0.814	-66	-0.663	-42	-0.422	-53	-0.532	-30	-0.296	-21	-0.208
$E_{\text{gas upgrading}}$	-18	-0.175	-18	-0.175	-18	-0.175	-18	-0.175	-18	-0.175	-14	-0.143
$E_{\text{vacuum collection}}$	-25	-0.25	-25	-0.25	-25	-0.25	-25[2]	-0.25[2]	-25[2]	-0.25[2]	0	0
$E_{\text{grass silage cultivation}}$	-3	-0.029	-3	-0.029	-3	-0.029	-3	-0.029	-3	-0.029	-3	-0.029
$E_{\text{indirect energy savings}}$	14	0.136	14	0.136	14	0.141	15	0.145	15	0.145	0	0
E_{total}	**149**	**1.489**	**164**	**1.64**	**189**	**1.886**	**178**	**1.780**	**202**	**2.016**	**177**	**1.768**

[1] UASB suitability needs to be confirmed, and methane producition may be lower [2] No data, estimated according to vacuum collection for comparison

Energy balance

Energy balances were calculated for the most realistic options (Table 8). The highest energy balances were obtained with a dry toilet system with urine separation (2.027 GWh/a for 10,000 people) and a vacuum toilet having 0.25 L flush volume and urine separation (1.791 GWh/a for 10,000 people). The highest energy consumption comes from parasitic energy demand in a AD plant (hygienization at 70 ºC). Also, the vacuum collection is estimated to be relatively energy-hungry, but it must be kept in mind that the value is only a rough estimation, as no large-scale examples exist.

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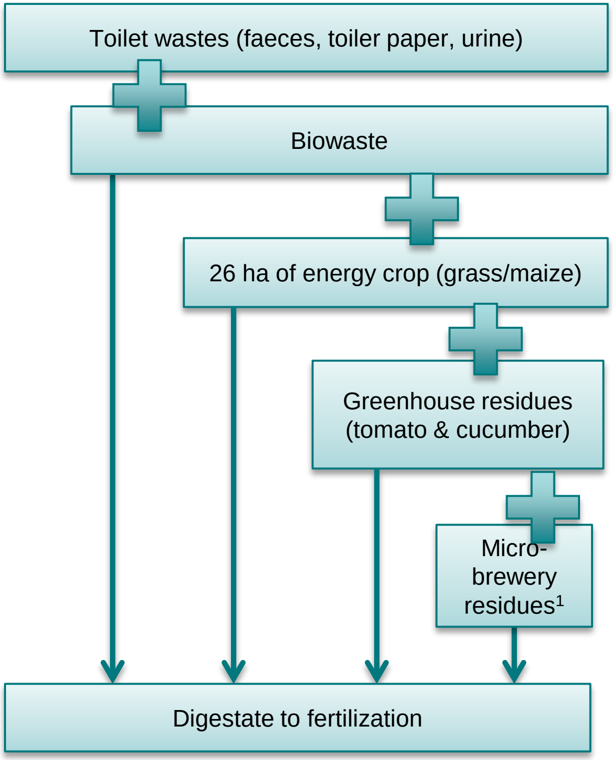
- Digestate Utilization Options

7. Digestate Utilization Options



Toilet wastes (faeces, toiler paper, urine)

Biowaste

26 ha of energy crop (grass/maize)

Greenhouse residues (tomato & cucumber)

Micro-brewery residues[1]

Digestate to fertilization

Figure 16: The studied composition of the digestate with different co-feedstock combinations

At the beginning of the food chain, current agriculture depends on artificial fertilizers that are produced in an energy-intensive process (nitrogen, N) (Brentrup & Palliére, 2008) and mined from scarce reserves (phosphorus, P) (Cordell & White, 2015). Agricultural products, and consequently food products, contain high amounts of nutrients that the human body mainly excretes in urine (Spångberg, 2014). In addition, garden and kitchen waste (bio-waste) contributes to urban nutrient flow (Sokka et al., 2004).

The fertilization potential of the digestate formed in the AD plant was studied. In the base scenario, the plant feedstocks and co-feedstocks (Figure 16) were:

a) Toilet waste and biowaste

b) Toilet waste, biowaste + energy crop (grass/maize)

c) Toilet waste, biowaste + energy crop + greenhouse residues

d) Toilet waste, biowaste + energy crop + greenhouse residues + brewery residues

The digestate nutrients from each case were assumed to be utilized in the fertilization of grain fields, as well as energy crops and greenhouse vegetables if these co-feedstocks were used. Furthermore, we studied three additional scenarios and their effect on the fertilization potential of the digestate:

1) No toilet waste (slide 28)

2) Urine separation with a 0.25 L flushing toilet (75% urine removal, slide 29)

3) Effect of greenhouse size (3,000 vs 5,000 m^2 greenhouse, slide 30)

The aim was to analyze the potential of the utilization of digestate nutrients in agriculture and study the effect of different digester co-feedstocks on the digestate nutrient value and potential in crop fertilization. Special interest was paid to finding out if the digestate from the theoretical digester provides sufficient nutrients for the fertilization of the energy crops (to increase the energy potential of the digester) and for the fertilization of greenhouse-grown vegetables produced for the inhabitants of the city. Furthermore, we also studied the storage and transportation of the digestate to fertilized fields.

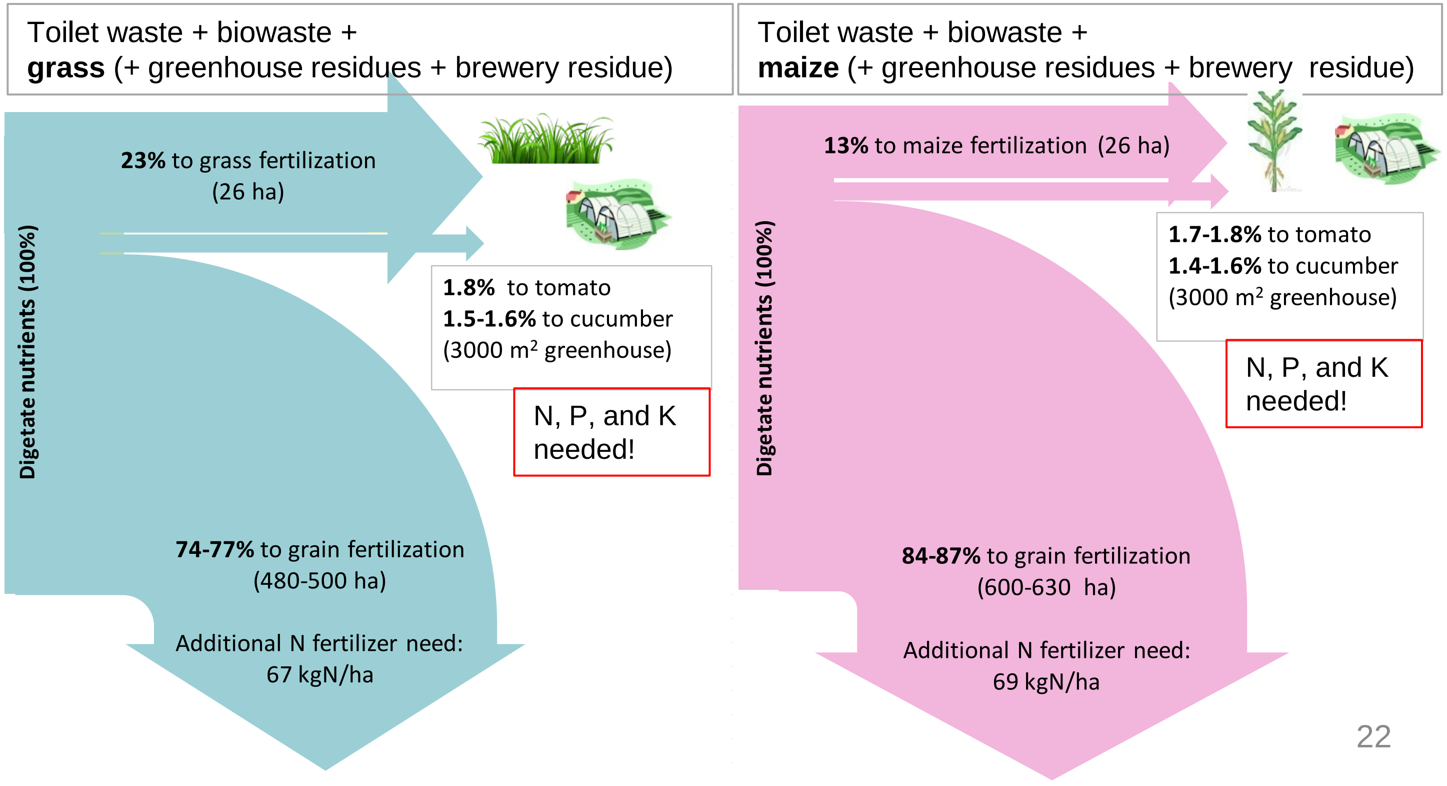
As the potential of the nutrient utilization was analyzed, all fertilization schemes are not necessarily applicable according the current Finnish legislation.

[1] Production of 500,000 L/a

Utilization of Digestate Nutrients (Base Scenario)

All of the digestate nutrients from the digestion of toilet wastes and biowaste only was assumed to be utilized in grain crops fertilization. When the biomass from the cultivation of energy crops (grass/maize) was added to the digester, the total amount of digestate nutrients increased, of which 23% could be used in the fertilization of grass (13% in the case of maize, Figure 17). The 3,000 m^2 greenhouse cultivation of tomatoes and cucumbers consumes <4% of the digestate nutrients with energy crop, greenhouse, and brewery residues as digester feedstock. The residual digestate was assumed to be used in the fertilization of grain crops outside the planned city area. The surrounding agricultural lands could use 74–77% or 84–87% of the digestate nutrients depending on the chosen energy crop. However, both greenhouse cultivation and grain fertilization need some additional nutrients (N, P, K) to supplement fertilization (see more detailed information on slides 24 and 25).

Figure 17: The nutrient flows in digestate utilization



Toilet waste + biowaste +
grass (+ greenhouse residues + brewery residue)

Digetate nutrients (100%)

23% to grass fertilization (26 ha)

1.8% to tomato
1.5-1.6% to cucumber
(3000 m^2 greenhouse)

N, P, and K needed!

74-77% to grain fertilization (480-500 ha)

Additional N fertilizer need: 67 kgN/ha

Toilet waste + biowaste +
maize (+ greenhouse residues + brewery residue)

Digetate nutrients (100%)

13% to maize fertilization (26 ha)

1.7-1.8% to tomato
1.4-1.6% to cucumber
(3000 m^2 greenhouse)

N, P, and K needed!

84-87% to grain fertilization (600-630 ha)

Additional N fertilizer need: 69 kgN/ha

Utilization of Digestate Nutrients (Base Scenario)

The digestate contains relatively similar amounts of nutrients in all studied AD co-feedstock combinations where the amount of nutrients is slightly increased along with the increased feedstock quantity, e.g., due to the introduction of energy crops and/or greenhouse and brewery residues. The applied and achieved fertilization levels with energy crop (grass), greenhouse vegetables (tomato, cucumber), and grain are presented in Table 9, and the applied and achieved fertilization level with the energy crop (maize), greenhouse vegetables (tomato, cucumber), and grain are presented in Table 10. Also, the need for supplementary fertilization is presented, as the digestates are not capable of fulfilling both the N and P needs of the crops, due to an uneven N/P ratio in relation to the crop need.

The use of maize as an energy crop compared to grass showed slight differences between studied cases, as the maize introduced more nutrients to the digestate. Compared to grass cases, the differences between nutrient utilization in fertilization (e.g., larger fertilization amounts for grains with maize as the energy crop) are due to the different fertilization levels between crops (250 $kgN_{soluble}$ for grass, 150 $kgN_{soluble}$ for maize). The relatively high P fertilization with both grass and maize was due to the high N fertilization rate, which was based on the Nitrate Decree (VNa 1250/2014). However, P fertilization did not exceed the legislative limit within the Fertilizer Product Decree (MMMa 24/11) (80 kgP/ha). Subsequently, due to the relatively high P fertilization level, no additional P supplementation was considered for grass or maize.

Overall, the digestate nutrients from different studied AD feedstock and co-feedstock cases can be utilized in the fertilization of energy crops and greenhouse vegetables in the studied region, while the residual digestate could be utilized in the fertilization of, e.g., grains in the nearby agricultural fields.

Utilization of Digestate Nutrients (Base Scenario)

Table 9: The digestate nutrient content, applied and achieved fertilization level, and the need for supplementary fertilization with toilet wastes and biowaste only and digester co-feedstocks (grass, greenhouse, and brewery residues)

	Toilet waste + biowaste	Toilet waste + biowaste + **grass**	Toilet waste + biowaste + **grass** + greenhouse	Toilet waste + biowaste + **grass** + greenhouse + brewery
Digestate nutrients (kg/cap)				
N	5.2	5.7	5.7	5.9
$N_{soluble}$	2.6	2.8	2.9	2.9
P	0.6	0.7	0.7	0.7
Fertilization of energy crops				
Area (ha)	-	26	26	26
Fertilization level (kg/ha)	-	$N_{soluble}$: 250 P: 58	$N_{soluble}$: 250 P: 58	$N_{soluble}$: 250 P: 58
Fertilization of greenhouse vegetables*				
Area (m^2)	-	-	2 x 1500	2 x 1500
Fertilization level (kg/m^2)	-	-	$N_{soluble}$: 0.3-0.35 P: 0.07-0.08	$N_{soluble}$: 0.3-0.35 P: 0.07-0.08
Need of nutrient supplements (kg/cap)		-	$N_{soluble}$: 0.01 P:0.05, K: 0.11	$N_{soluble}$: 0.02 P: 0.04, K: 0.11
Fertilization of grains				
Area (ha)	601	506	485	509
Fertilization level (kg/ha)	P: 10	P: 10	P: 10	P: 10
Need of nutrient supplements (kg/cap)	$N_{soluble}$: 4.0	$N_{soluble}$: 3.4	$N_{soluble}$: 3.2	$N_{soluble}$: 3.4
*Tomato and cucumber				

Utilization of Digestate Nutrients (Base Scenario)

Table 10: The digestate nutrient content, applied and achieved fertilization level, and the need for supplementary fertilization with toilet wastes and biowaste only and digester co-feedstocks (maize, greenhouse, and brewery residues).

	Toilet waste + biowaste + **maize**	Toilet waste + biowaste + **maize** + greenhouse	Toilet waste + biowaste + **maize** + greenhouse + brewery
Digestate nutrients (kg/cap)			
N	5.9	5.9	6.1
$N_{soluble}$	2.9	2.9	3.0
P	0.7	0.7	0.8
Fertilization of energy crops			
Area (ha)	26	26	26
Fertilization level (kg/ha)	$N_{soluble}$: 150 P: 37	$N_{soluble}$: 150 P: 37	$N_{soluble}$: 150 P: 37
Fertilization of greenhouse vegetables*			
Area (m^2)	-	2 x 1500	2 x 1500
Fertilization level (kg/m^2)	-	$N_{soluble}$: 0.28-0.35 P: 0.07-0.09	$N_{soluble}$: 0.28-0.35 P: 0.07-0.09
Need of nutrient supplements (kg/cap)		$N_{soluble}$: 0.02 P: 0.01, K: 0.11	$N_{soluble}$: 0.02 P: 0.01, K: 0.11
Fertilization of grains			
Area (ha)	627	605	629
Fertilization level (kg/ha)	P: 10	P: 10	P: 10
Need of nutrient supplements (kg/cap)	4.3	4.2	4.4
*Tomato and cucumber			

Utilization of Digestate Nutrients (Base Scenario)

The co-digestion of toilet waste with biowaste, energy crops, and residues from greenhouses and breweries showed potential for the fertilization of

- 26 ha of energy crops (grass/maize)
- 3,000/5,000 m^2 of greenhouse-grown vegetables sufficient for 10,000 inhabitants
- 400-600 ha of grain fields.

The average consumption of grains in Finland is 80 kg/cap/a (SVT, 2015a), and average crop yield is around 3,500 kg/ha (SVT, 2015b).
-> 400 ha of field produce around 1.4 Mkg of grains -> sufficient for 17,500 inhabitants.

The average grain consumption in breweries 2.2 kg/L product (Yara, 2015) -> 1.1 Mkg of grain needed to produce 500,000 L of beer in the micro-brewery.
-> With the average grain yield of 3,500 kg/ha (SVT, 2015b), 400 ha of grain fields can produce 130% of grains for the brewery.

Supplementary fertilization

Supplementary fertilization is still needed to supplement the fertilization in greenhouse and grain cultivation. In greenhouses, the digestate fertilization is capable of meeting 100% of $N_{soluble}$ and 90-99% of P fertilization in tomatoes. In cucumber fertilization, digestate accounts for 70-75% of $N_{soluble}$ and 100% of P fertilization. With both cucumber and tomatoes, the digestate accounts for 64-71% of the K fertilization. Overall, 0-30% of the vegetables nutrient need must be supplemented with mineral fertilizers.

In the fertilization of grains, the P need of the crops is fully satisfied with the digestate, while the digestate accounts for around 40% of the crop N need. Subsequently, 61-63% of the crop nutrient need must be supplemented with mineral nitrogen fertilizers or processed organic fertilizers.

Digestate Usability as a Fertilizer in Agriculture

$N_{soluble}/P$ ratio of digestates

The ratio between soluble N and total P was around 4 in the studied digestates originating from the digestion of toilet waste, biowaste, energy crops, and greenhouse and brewery residues. However, crop cultivation usually has need of higher $N_{soluble}/P$ ratios based on the fertilization rates (Table 11). The high need of N compared to P in crops increases the need for supplementary N fertilization.

Greenhouse-grown vegetables (e.g., tomatoes and cucumbers) have a lower need of N in relation to P, which leads to a lower N/P ratio need with these vegetables (around 5, Table 13). As it follows, the digestates could be more suitable fertilizers for greenhouse use, with lower need of supplementary N. However, the current legislation prevents the use of wastewater sludge-based digestates on commercial edible vegetables, while it is allowed on crops, e.g., grains (VNp 282/1994; MMMa 24/11).

Table 11: The $N_{soluble}/P$ ratios for different crops

Crop	$N_{soluble}/P$
Grains*	11
Tomato	4
Cucumber	5.7
Grass*	7
Maize*	9

*If fertilized according to the Agri-Environmental support system (MAVI, 2015).

$N_{soluble}/P = 4$ in digestates

Challenges and risks of digestate use

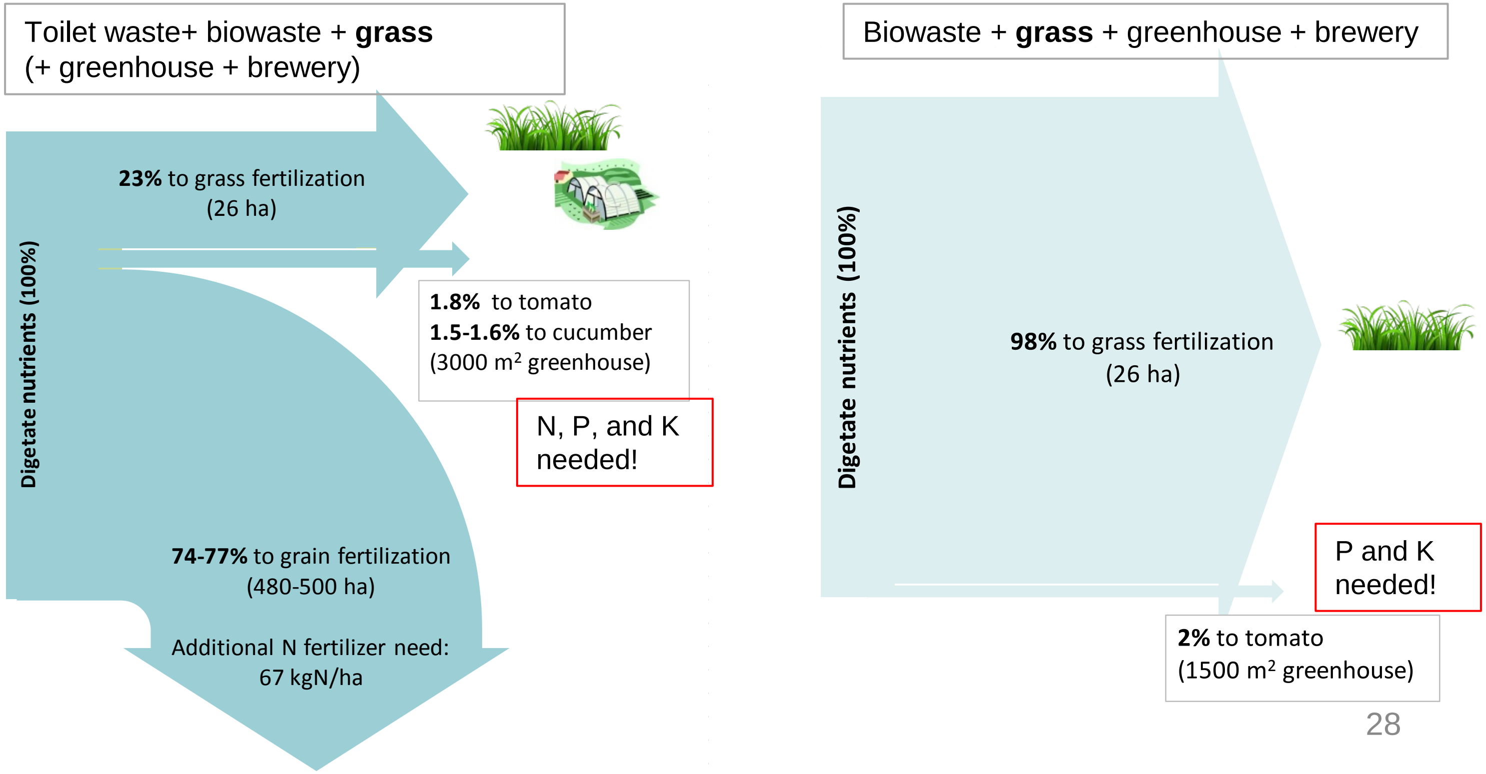
The use of digestates as fertilizers in agriculture can increase the risk of contamination due to, e.g., organic contaminants, heavy metals, and pharmaceuticals, depending on the digestate feedstock. In recent years, many publications about the risks related to the use of biowaste and municipal wastewater treatment sludge have been made. According to their risk assessments, the use of municipal waste biomasses does not pose a threat to human health (Kraus, 2015; Marttinen et al., 2014; Vieno, 2015). In addition, the anaerobic digestion process further decreases the concentrations of many pharmaceutical compounds in digester feedstocks. Overall, the risk arising from the use of municipal wastes as a feedstock for the digestion process and fertilizer use can be minimized by using fertilizer products according to the existing regulations and legislation. The foremost solution for decreasing the risk of digestate fertilization is the prevention of contamination already in the consumer stage to ensure safe fertilizer use and food production using organic recycled nutrients.

Digestate without Toilet Wastes (Scenario 1)

If toilet waste is not treated in the same anaerobic digester as energy crops, greenhouse, and brewery residues, the total mass and nutrient flow of the digestate decreases 75–77%. The reduced digestate volume and nutrients are sufficient for the fertilization of grass. However, there is not enough material for the fertilization of both tomatoes and cucumbers in the greenhouse, where, for example, only tomatoes can be fertilized (Figure 18).

If toilet wastes (human excreta, toilet paper, and urine) are not treated in digesters, 98% of the digestate nutrients are used in the fertilization of energy crop (grass), while around 2% of the nutrients can be used in the greenhouse to fertilize tomatoes (greenhouse area for tomatoes = 1,500 m²). The fertilization of tomatoes still requires some supplementary P and K fertilization.

With a greenhouse area of 5,000 m², the amount of vegetable residues is slightly higher, increasing the digestate volume and nutrient amount. With larger greenhouse areas, more of the cultivated vegetables can be fertilized with the produced digestate.



Toilet waste+ biowaste + **grass** (+ greenhouse + brewery)

Digetate nutrients (100%)

23% to grass fertilization (26 ha)

1.8% to tomato
1.5-1.6% to cucumber
(3000 m² greenhouse)

N, P, and K needed!

74-77% to grain fertilization (480-500 ha)

Additional N fertilizer need: 67 kgN/ha

Biowaste + **grass** + greenhouse + brewery

Digetate nutrients (100%)

98% to grass fertilization (26 ha)

P and K needed!

2% to tomato (1500 m² greenhouse)

Figure 18: The nutrient flows in digestate utilization with and without toilet waste collection

Effect of Urine Separation on the Fertilizer Potential of the Digestate (Scenario 2)

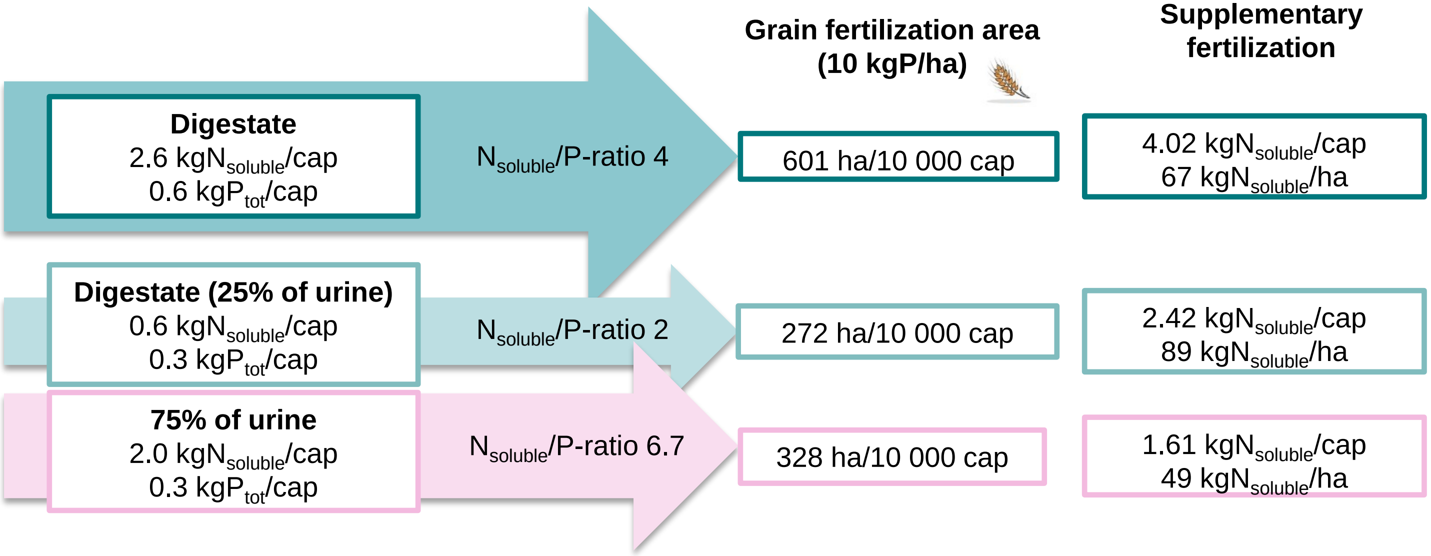
Digestate from digesters treating only toilet wastes and biowaste can be spread on 600 ha of grain crops to fulfill the P need of the crop. If, e.g., 75% of the urine can be separated with the chosen toilet system (vacuum toilet with 0.25 L flush), the amount of nutrients in the digestate decreases 50-70% and around 50% less agricultural land is needed for the utilization of the digestate (Figure 19).

However, the urine contains high amounts of N and P, which could be utilized in agriculture without anaerobic digestion. The sole urine could be used to fertilize 330 ha of grain fields, which lowers supplementary nitrogen fertilizer need compared to the digestate and digestate without urine.

The separation of urine decreases the $N_{soluble}/P$ ratio of the digestate from 4 to 2, which affects the need for supplementary nitrogen fertilizers. The raw urine contains a high $N_{soluble}/P$ ratio (7), which is similar to the fertilization regimes of grass and maize (see Table 13).

The use of sole urine in vegetable fertilization has been reported (e.g., in Pradhan, 2010), where it has been proven a comparable fertilizer with mineral fertilizers. Similar concerns have arisen from the use of urine in fertilization as from the use of digestates (e.g., microbiological risks, content of pharmaceuticals), which could be prevented with technical solutions. Currently the Finnish legislation prevents the use of urine as a commercial fertilizer.

Figure 19: The nutrient flows in digestate utilization with and without urine collection

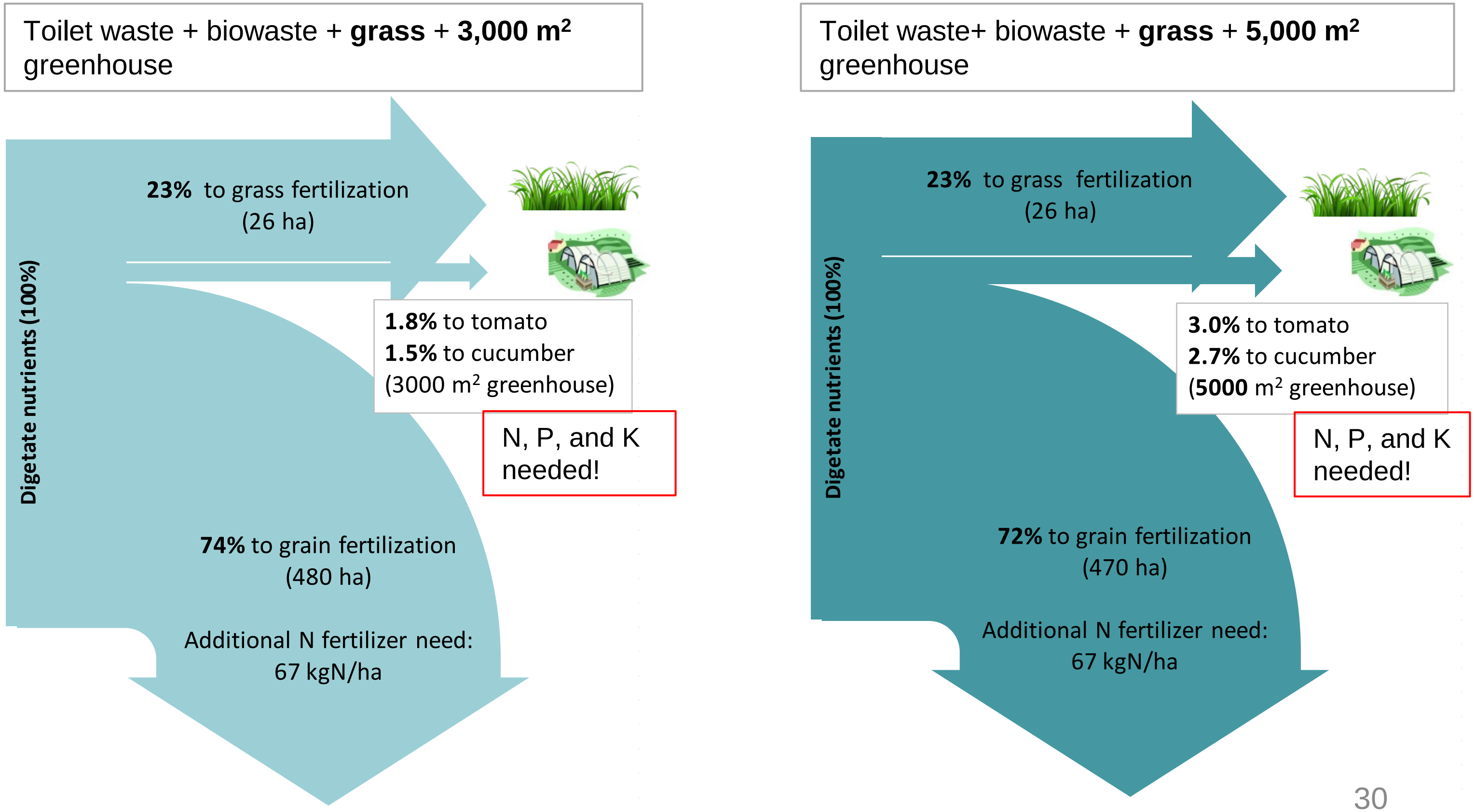


		Grain fertilization area (10 kgP/ha)	Supplementary fertilization
Digestate 2.6 $kgN_{soluble}$/cap 0.6 kgP_{tot}/cap	$N_{soluble}$/P-ratio 4	601 ha/10 000 cap	4.02 $kgN_{soluble}$/cap 67 $kgN_{soluble}$/ha
Digestate (25% of urine) 0.6 $kgN_{soluble}$/cap 0.3 kgP_{tot}/cap	$N_{soluble}$/P-ratio 2	272 ha/10 000 cap	2.42 $kgN_{soluble}$/cap 89 $kgN_{soluble}$/ha
75% of urine 2.0 $kgN_{soluble}$/cap 0.3 kgP_{tot}/cap	$N_{soluble}$/P-ratio 6.7	328 ha/10 000 cap	1.61 $kgN_{soluble}$/cap 49 $kgN_{soluble}$/ha

Effect of Greenhouse Size on Nutrient Utilization (Scenario 3)

The increase of greenhouse size from 3,000 to 5,000 m^2 increases the amount of greenhouse residues and the nutrients within the digestate by 0.1-0.2%. However, as the greenhouse area doubles, the fertilizable area is also doubled, and fertilizer need is increased. With larger greenhouse areas, around 6% of the digestate nutrients are utilized in the greenhouse (2% increase compared to 3,000 m^2 greenhouse) (Figure 20). However, there is still potential to use 72% of the digestate nutrients in grain fertilization.

Figure 20: The nutrient flows in digestate utilization with greenhouse sizes 3,000 and 5,000 m^2



Toilet waste + biowaste + **grass** + **3,000 m^2** greenhouse

Digetate nutrients (100%)

23% to grass fertilization (26 ha)

1.8% to tomato
1.5% to cucumber
(3000 m^2 greenhouse)

N, P, and K needed!

74% to grain fertilization (480 ha)

Additional N fertilizer need: 67 kgN/ha

Toilet waste+ biowaste + **grass** + **5,000 m^2** greenhouse

Digetate nutrients (100%)

23% to grass fertilization (26 ha)

3.0% to tomato
2.7% to cucumber
(**5000** m^2 greenhouse)

N, P, and K needed!

72% to grain fertilization (470 ha)

Additional N fertilizer need: 67 kgN/ha

Digestate Transportation and Storage

(10,000 Inhabitants, 0.25 L Flushing Toilet)

The digestate was assumed to be transported different distances depending on the fertilized crop (Figure 21). The energy crop fields and greenhouses were assumed to be located within a distance of 5 km from the AD plant. The digestate aimed for the fertilization of these crops was stored at the AD plant and transported with a tractor. The digestate aimed for the fertilization of grain fields was stored at farms, which were located within 20 km. The transportation was executed with a semi-trailer truck. Additionally, the transportation from the farm storage to the fields (5 km) was calculated using the energy consumption of a tractor. Empty returns were taken into consideration with all vehicles and distances. The energy consumption of the transportation, as well as the storage capacity needed for 12 months of digestate storage, are presented in Table 12.

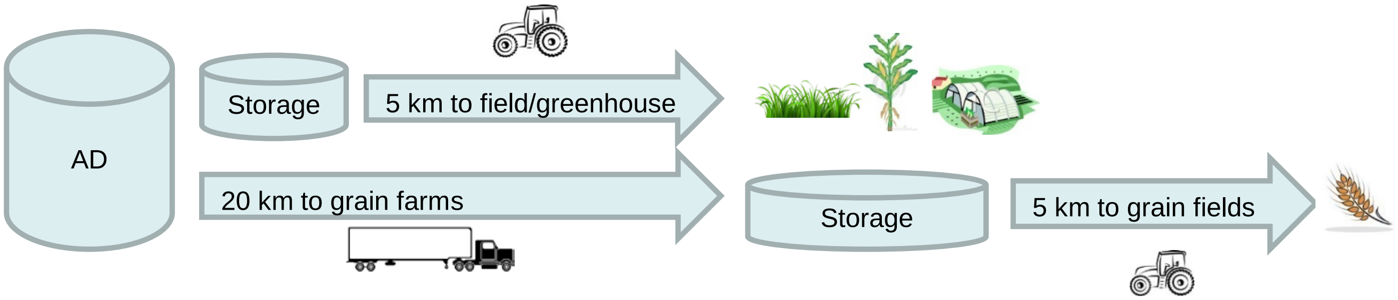


Figure 21: Transportation distances for digestates

Table 12: The energy consumption of digestate transportation and the storage capacity needed for 12 months' storage

Digester feedstock	Toilet waste + biowaste						
Digester co-feedstock(s)	-	Grass	Grass + greenhouse residue	Grass + greenhouse + brewery residue	Maize	Maize + greenhouse residue	Maize + greenhouse + brewery residue
Transportation							
Total consumption (MWh/a)	164.9	150.1	183.8	153.9	183.8	180.8	184.1
% of energy content of feedstocks	9.9	6.1	5.6	5.9	5.6	5.5	5.3
Need of storage capacity (m³/a)							
At AD plant (for energy crops/vegetables fertilization)	-	5 600	2 600	5 400	2 600	3 300	3 200
At farm (for grain fertilization)	14 700	10 100	14 000	10 500	14 100	13 500	13 700

Grass/Maize 26 ha, greenhouse 3,000 m², brewery production 500,000 L/a

8. Conclusions

This study presented various scenarios for distributed biogas production and resource recovery in the theoretical new residential area with 10 000 inhabitants, energy crops (26 ha grass/maize), 3000 m^2 greenhouse for cucumber and tomatoes cultivation and local services (brewery, 100 000 L/a). The utilization of household waste (toilet waste and biowastes) was studied as a base scenario and the potential of energy crops, greenhouse and brewery residues in biogas production and in nutrient circulation was evaluated.

The summary of the distributed biogas production :

- Biogas energy potential is in the biowaste and plant biomass, while nutrients are mainly in the urine.
- The infrastructures for the toilet flush water decrease as well as grey water and urine separation are potential measures to decrease the treated waste volume, and subsequently the volume of the biogas reactor.
- The biogas can supply gas cookers in all households in the area or to supply biomethane for nearly 300 vehicles (assumed driving of 20 000 km/a).
- Total primary biogas production potential is about 1% total per capita energy consumption, or 3–4% of heat and electricity production in the residential area as based on present average consumption in cities. The percentage is expected to be higher in new modern energy efficient residential areas.

The summary of the digestate utilization:

- Biogas process' nutrients in the digestates can be utilized for the cultivation of energy crops (grass/maize) and greenhouse vegetables in the residential area as well as for the production of grains in nearby farms. In the farms, the fertilization potential is sufficient for the production of grains for 17,500 inhabitants. However, nitrogen fertilizer supplementation is needed in crop production, as the nitrogen / phosphorous ratio is too low for crop production.
- Digestate storage capacities of 2,600–5,600 m^3 for digestates are needed at the AD plant and 10,000–15,000 m^3 in the farms.
- Transportation of the digestates consumes 5 to10% of the primary biogas production.

9. Materials and Methods: Resource Recovery Potentials

Table 13: Used values to calculate resource recovery potentials in this study

	Production	TS	VS	N tot	P tot	K tot	BMP	Ref.
	kg/cap/a	%	%	g/kg TS	g/kg TS	g/kg TS	L CH$_4$/kg VS	
Grey water	47450	0.06	0.03	21.5	9.6	11	n.a.	[1]
Faeces	58.4	32	28	28	9.4	19	280	[1,2]
Urine	550	1.3	0.5	550	45	41	n.a.	[1]
Kitchen waste	80.3	30	26	25	3.8	9.2	500	[1,3]
Grass silage	10[a]	27	25	20.2	2.1	5	323	[4,5,6]
Maize	17[a]	22	20	14.7	2.8	5	396	[4,5]
Greenhouse tomato residues	16[b]	11	9	23	1.8	20	320	[7,8,9]
Greenhouse cucumber residues	31[c]	9	8.5	21.8	1.8	20	260	[7,8]
Brewery waste	167[d]	30	27	38	5	5	390	[10]

[a] t TS/ha

[b] t fresh biomass/a (calculated assuming residual biomass 24% of produced tomato (an expert estimation))

[c] t fresh biomass/a (calculated assuming residual biomass 28% of produced tomato (an expert estimation))

[d] fresh biomass/a (calculated assuming residual biomass 33% of beverage production (an expert estimation))

[1] Jönsson et al., 2005
[2] Rajagopal et al., 2013
[3] Mönkäre et al., 2015
[4] Seppälä, 2013
[5] Bulkowska et al., 2012
[6] Platace et al., 2013
[7] Luke (expert estimation)
[8] Jagadabhi et al., 2011
[9] Li et al., 2016a
[10] Oreopoulou & Russ, 2007

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9. Materials and Methods: Resource Recovery Potentials

Table 14: Used energy consumption values for wastewater treatment, water purification, and pumping

	Wastewater treatment (kWh/m^3)^a	Water purification (clean water production) (kWh/m^3)	Water pumping (avg.) (kWh/m^3)	Ref.
HSY (avg. 2009-2013)	0.282	0.52	-	HSY, 2015
Tampereen Vesi (2013 ja 2014)	0.27	0.52	0.17	Tampereen Vesi, 2014
Average	**0.28**	**0.52**	**0.17**	

a Energy production reduced (biogas from excess sludge)

Table 15: Used values for consumer prices of clean water and wastewater

	Wastewater consumer price (e/m^3)	Clean water consumer price (e/m^3)	Ref.
Helsinki	1.38	1.70	HSY, 2016
Tampere	1.43	2.06	Tampereen Vesi, 2016
Average	**1.41**	**1.88**	

Table 16: Used energy consumption values for vacuum toilet collection of toilet waste, grass silage cultivation, and biogas upgrading

	Energy consumption	Ref.
Vacuum toilet collection (kWh/cap/a)	25	Tervahauta, 2014
Grass silage cultivation (chemicals excluded) (MWh/ha)	1.12	Mikkola & Ahokas, 2009
Biogas upgrading to biomethane (kWh/m^3)	0.28	Expert estimation: Schmack Carbotech GmbH, BioGTS Oy

9. Materials and Methods: Resource Recovery Potentials

The energy balance of AD, including hygienization steps, was estimated using following equations:

$$E_{i,heat} = \rho Q\gamma(\mathrm{T}_p - \mathrm{T}_a) + \mathrm{k}\mathrm{A}_p(\mathrm{T}_p - \mathrm{T}_a) - \rho Q\gamma(\mathrm{T}_p - \mathrm{T}_d)\phi + \mathrm{k}\mathrm{A}_d(\mathrm{T}_p - \mathrm{T}_a)$$

where $E_{\mathrm{i,heat}}$: input heat (kJ d^{-1}); ρ: density (kg m^{-3}); Q: flow rate (m^3 d^{-1}); γ: specific heat (kJ kg$^{-1\circ}$ C^{-1}); T_{p}: pretreatment temperature; T_{a}: ambient temperature; T_{d}: anaerobic digestion temperature; k: heat transfer coefficient (Wm$^{-2\circ}$ C^{-1}); A_{p}: surface area of the pretreatment reactor wall (m^2); A_{d}: surface area of the digester reactor wall (m^2); and ϕ: heat recovery efficiency.

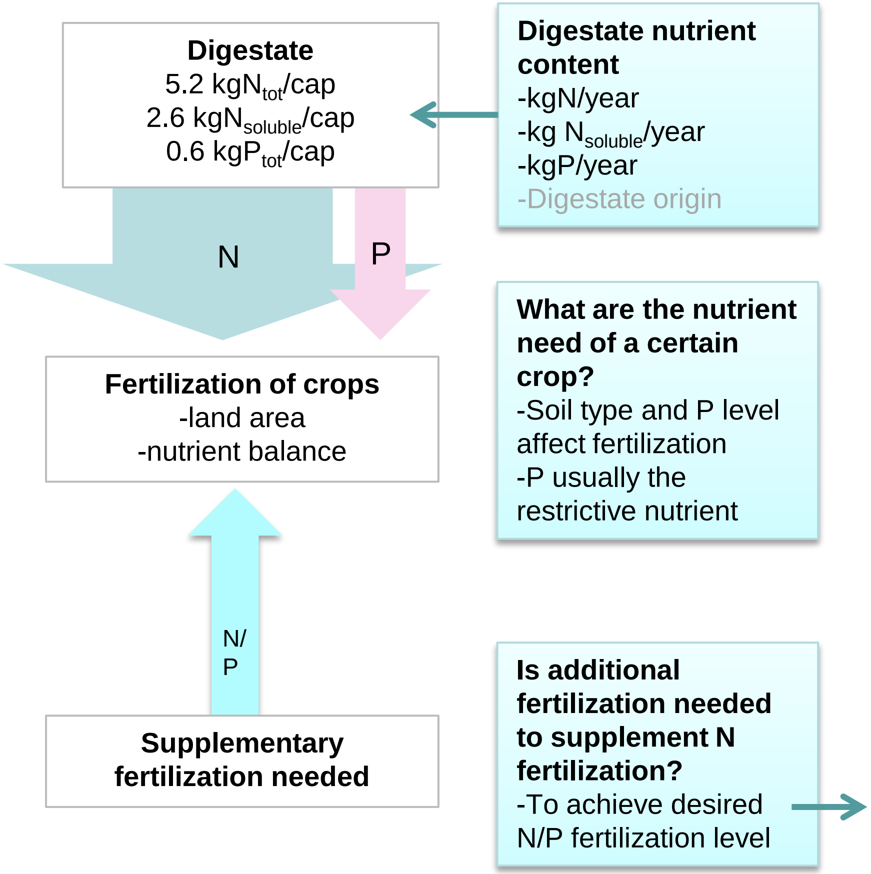
$$E_{i,electricity} = Q\theta + \mathrm{V}\omega \qquad (5)$$

where $E_{\mathrm{i,electricity}}$: input electricity (kJ d^{-1}); Q: flow rate (m^3 d^{-1}); θ: electricity consumption for pumping (kJ m^{-3}); V: useful volume (m^3); and ω: electricity consumption for mixing (kJ m$^{-3}_{\mathrm{reactor}}$ d^{-1}).

Table 17: Parameters used to calculate the energy balances

	Unit	Value	Reference
Parameter			
Density of water (ρ)	kg m^{-3}	1000	Passos & Ferrer, 2014
Specific heat of water (γ)	kJ kg^{-1}°C	4.18	Passos & Ferrer, 2014
Heat transfer coefficient (k)	W m^{-2}°C	1	Passos & Ferrer, 2014
Heat recovery by heat exchanger (φ)	%	85	Passos & Ferrer, 2014
Electricity consumption for pumping (θ)	kJ m^{-3}	1800	Passos & Ferrer, 2014
Electricity consumption rate for mixing (ω)	kJ m^{-3}·d	300	Passos & Ferrer, 2014
Lower heating value of methane	kWh m^{-3}	9.94	Passos & Ferrer, 2014
Ambient temperature (Central Finland) (T_a)	°C	4	
Anaerobic digestion temperature (T_d)	°C	35	
Hygienization temperature (T_p)	°C	70	

9. Materials and Methods: Nutrients and Fertilization of Crops



Digestate
5.2 kgN_{tot}/cap
2.6 kg$N_{soluble}$/cap
0.6 kgP_{tot}/cap

Digestate nutrient content
-kgN/year
-kg $N_{soluble}$/year
-kgP/year
-Digestate origin

N

P

Fertilization of crops
-land area
-nutrient balance

What are the nutrient need of a certain crop?
-Soil type and P level affect fertilization
-P usually the restrictive nutrient

N/
P

Supplementary fertilization needed

Is additional fertilization needed to supplement N fertilization?
-To achieve desired N/P fertilization level

Figure 22: Approach for the calculation of the digestate fertilization potential

Background and assumptions

Nutrients from the digester feedstock are conserved in the digestate. Of the total N, 50% was assumed to be in soluble form (soluble nitrogen, $N_{soluble}$).

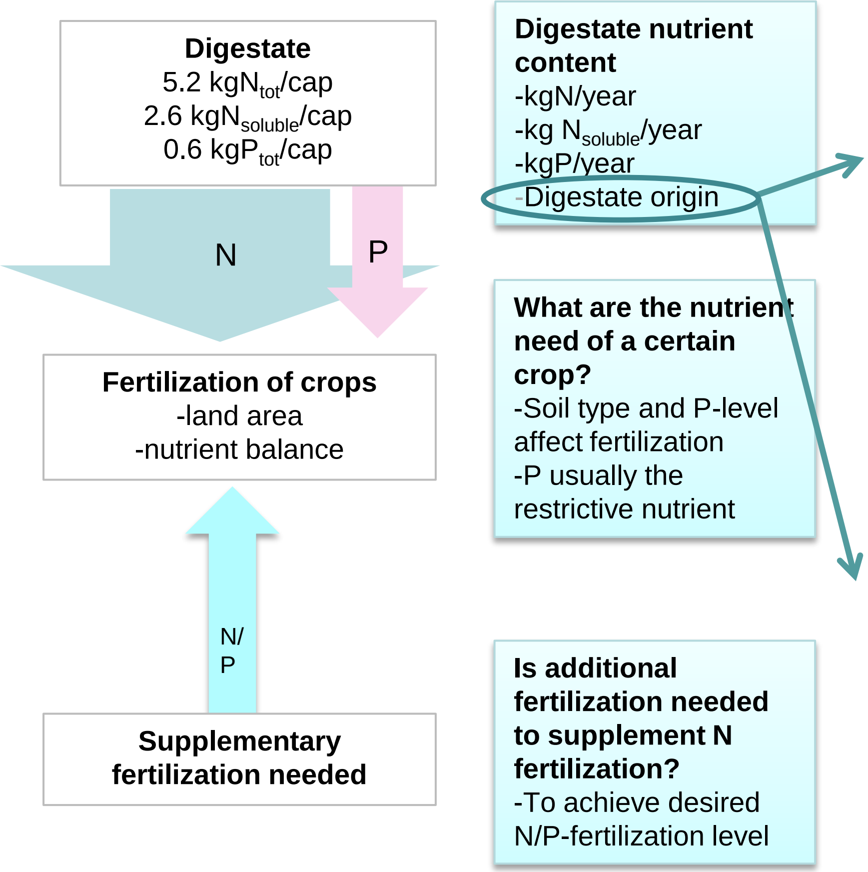
The digestate was assumed to be used as a fertilizer in crop production (Figure 22). The chosen crop was grain, which can be fertilized with digestates originating from municipal wastewater treatment (VNp 282/1994). Additionally, the digestate was assumed to be used for the fertilization of the energy crops (grass/maize) and greenhouse-grown vegetables (tomato and cucumber). The residual digestate was assumed to be used for the fertilization of grain.

The fertilization of grains was based on the fertilization levels from the Finnish Agri-Environmental support system (MAVI, 2015) and on the average soil type in Finland (P-level "satisfactory" and soil type "rich loamy"). For grass and maize, the N fertilization limit from the Nitrate Decree (VNa 1250/2014) and P limit from the Fertilizer Product Decree (MMMa 24/11) were used, as the cultivation of these crops was assumed to be executed without the Agri-Environmental supports. Vegetable fertilization was based on the common fertilizer use in greenhouses. The following fertilization levels were used:

- Grains: 10 kgP/ha, 110 kgN/ha
- Grass: max 80 kgP/ha, 250 kgN/ha
- Maize: max 80 kgP/ha, 150 kgN/ha
- Tomato: 0.0875 kgP/m^2, 0.35 kgN/m^2, 0.56 kgK/m^2
- Cucumber: 0.07 kgP/m^2, 0.4 kgN/m^2, 0.55 kgK/m^2

The fertilization was based on either $N_{soluble}$ or P level within the digestates. If the level of $N_{soluble}$ or P was not fulfilled with the N from the digestate, additional (mineral) fertilizers were needed to supplement the fertilization.

9. Materials and Methods: Nutrients and Fertilization of Crops



Digestate
5.2 kgN_{tot}/cap
2.6 kg$N_{soluble}$/cap
0.6 kgP_{tot}/cap

Fertilization of crops
-land area
-nutrient balance

Supplementary fertilization needed

Digestate nutrient content
-kgN/year
-kg $N_{soluble}$/year
-kgP/year
-Digestate origin

What are the nutrient need of a certain crop?
-Soil type and P-level affect fertilization
-P usually the restrictive nutrient

Is additional fertilization needed to supplement N fertilization?
-To achieve desired N/P-fertilization level

Figure 23: Approach for the calculation of the digestate fertilization potential

Digestate origin was not considered to affect fertilization use/potential

The current Finnish legislation (VNp 282/1994, MMMa 24/11) does not allow the fertilization of edible plants with organic materials originating from municipal wastewater treatment. Furthermore, the fertilization of grass with wastewater sludge is limited, and sludge fertilization is allowed only during the first year of the grass fertilization cycle (Figure 23).

In this study, the grass fertilized with the digestates was assumed to be fed as an energy crop to the digester, and thus the restrictions related to the grass fertilization were not taken into consideration. The greenhouse-grown vegetables (tomato and cucumber) were assumed to be fertilized with the digestates, despite the restrictive legislation.

The current legislation limits the P fertilization, where only 60% of the P in the wastewater-based fertilizers is taken into account (MAVI, 2015), as the P availability is limited due to the chemical precipitation process during wastewater treatment. In this study, these restrictions were not taken into consideration, the nutrients from toilet waste were utilized after anaerobic digestion, and no conventional wastewater treatment processes were applied. As it is, the availability of the P within the digestates is most likely high.

9. Materials and Methods: Transportation and Storage

The energy consumption of the digestate transportation was based on the assumed transportation distances and energy consumption of a tractor and semi-trailer truck (Table 18). It was assumed that the fields in which the energy plants (grass and maize) are farmed are located in distance of 5 km from the AD plant, where digestate is transported by tractor. The residual digestate is transported 20 km by semi-trailer trucks to storage at farms, from which the digestate is transported 5 km to the grain fields. Empty returns are taken into consideration with both tractors and semi-trailer trucks.

The mass of the digestate was assumed to be the same as the total mass of the AD plant feedstocks.

The digestate storage time of 12 months was used, as the digestate fertilization is in practice once a year according to the legislation (VNa 1250/2014).

Table 18: The literature values obtained for the calculation of the energy consumption of the digestate transportation

	Distance	Load	Energy consumption, full	Energy consumption, empty	References
Tractor	5 km	12 t	0.2 L/tkm	0.2 L/km	Marttinen et al., 2015; Posio, 2010
Semi-trailer truck[a]	20 km	25 t	4.1 kWh/km	3.0 kWh/km	VTT Lipasto, 2012

[a]Euro 6

Infrastructure Planning (City of Tampere)

1. Summary: Infrastructure planning (City of Tampere)

Urban water and waste and energy sectors in high-income countries are characterized by central plants and long distribution networks. Socio-technical transition to more sustainable infrastructures is expected to include partial decentralization based on local conditions. In this task, we aim is to understand what kind of city planning enables alternative infrastructure solutions, and what the characteristics are of an alternative concept capable of a breakthrough. We look at socio-technical transition from a multi-level perspective (Introduction).

Seventeen water, waste, gas, energy, and city planning experts were interviewed, and the data were analyzed qualitatively. In addition, seven experts attended a workshop, where interview results were discussed and developed further (Methods).

We grouped data into drivers, barriers, and enablers for implementing a decentralized circular system in a new residential area. Results are presented under seven central themes raised from research data: interactive planning process and role of actors, information production and sharing, environmental values, technical development and cost efficiency, operations models, suitable areas, and local benefits (Drivers, Barriers, and Enablers).

Results indicate that sustainability transition in the infrastructure sector can be facilitated by impartial city planning that allows early participation of different actors; improved interaction between actors and within city organizations; studying economic, environmental, and social effects of alternative solutions; and city guidance according to environmental policy aims. Alternative solution success factors include suitable locations, professional partners in each part of the industrial ecosystem, mature technology, and visible local benefits (How Can We Facilitate Socio-Technical Transition?).

Keywords: sustainable infrastructure, alternative sanitation, small-scale biogas plant, nutrient recycling, urban land-use planning

2. Introduction

Recently, infrastructure sectors have experienced increasing environmental and economic pressure to renew their organizing principles and technologies (Fuenfschillinger & Truffer, 2016). Decentralization has the potential to improve nutrient recycling and energy efficiency (Tervahauta et al., 2013), reduce infrastructure costs and support innovations that can be exported to emerging economies (Quezada et al., 2016), increase renewable energy production capacity and energy self-sufficiency (Ruggiero et al., 2015), and enhance sustainability in terms of flexibility, locality, and networking (Alanne & Saari, 2006).

Socio-technical transition towards sustainable infrastructures requires pressure from the landscape and potential and mature niche innovations, which can destabilize dominant regime practices (Figure 24). The research objective is to find preconditions for alternative concept implementation. The research questions are as follows: How can a decentralized circular system be supported in the context of urban planning? What are the characteristics of an alternative system capable of breaking through?

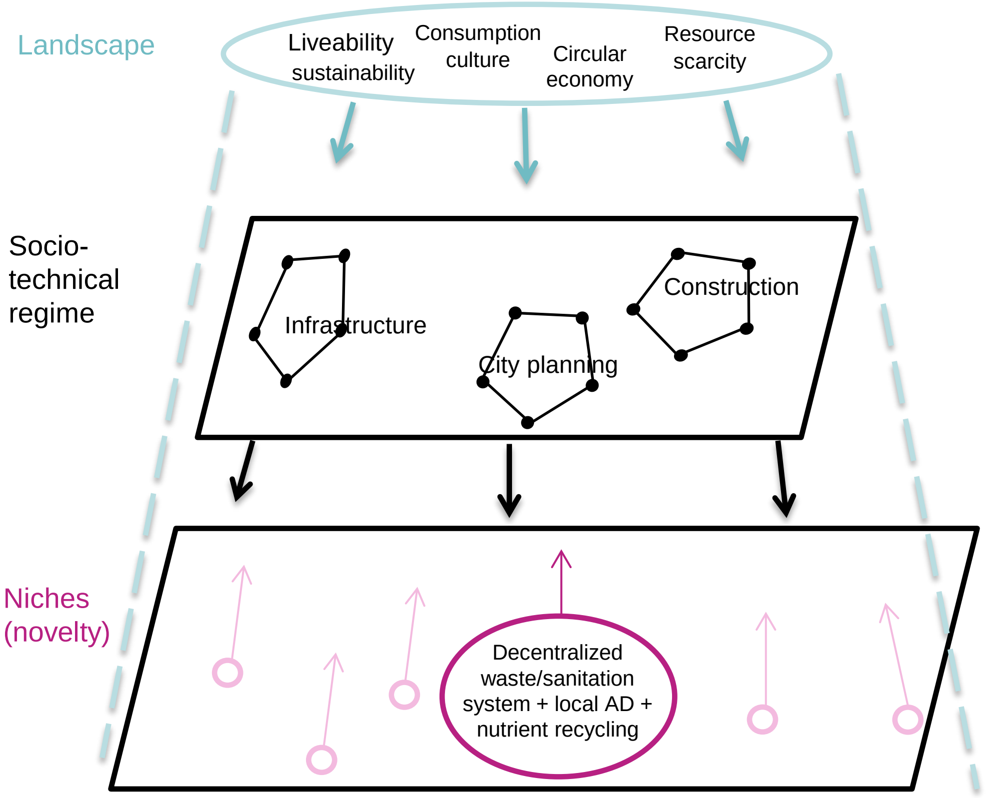


Figure 24: Decentralized circular system (niche); dominant means of realizing water, waste, and energy infrastructure in new residential areas (regime); and external factors (landscapes), such as lifestyles and political ambitions that shape cities; multi-level perspective (Geels, 2010)

3. Methods

Data from 17 interviews and a workshop (Figure 25)

- Themes of the semi-structured interviews: experience in new area development, actors' potential roles if the studied system was implemented, agencies' roles in city planning, and narratives of successful/unsuccessful innovations.
- In workshops, drivers, barriers, and enablers of alternative solution implementation (interview results) were discussed and developed. Participants selected the key issues that should be emphasized in this study and further research.

Analysis

- Directed content analysis (Hsieh & Shannon, 2005).
- Grouping data into drivers, barriers, and enablers (Quezada et al., 2016).
- Results were organized according to a multi-level perspective on socio-technical transitions (Geels, 2010).

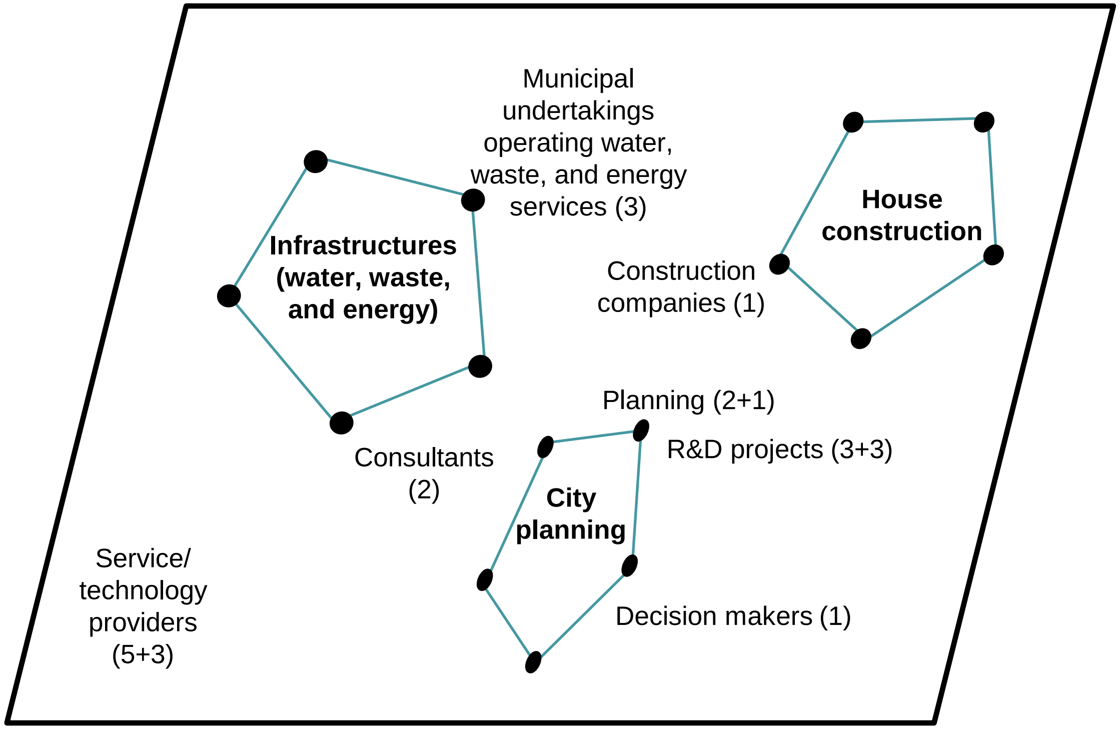


Figure 25: Participating water, waste, gas, energy, and city planning experts (number of interviewees + workshop attendees)

4. Drivers, Barriers, and Enablers of Alternative System Implementation

Seven themes raised from interviews and workshops

Urban planning process that enables innovations

1. Interactive planning process and roles of actors
2. Information production and sharing
3. Environmental values

Sustainability innovation compatible for breakthroughs

4. Technical development and cost efficiency
5. Operations model
6. Suitable area
7. Local benefits

The seven themes are described in the next slides.

> *"In new area planning, there are so many things that it is easy to choose old system here. New invites people to complain and slow down the process. Sometimes we study new ideas, but they are not implemented because residents or other city officers are against them."* (Consultant)

Drivers, Barriers, and Enablers

“Actors think their own benefit, not an overall picture, for example HSY uses biogas in its own CHP plant, even though better for whole system would be to use it as gas somewhere else.” (Technology/service provider)

1. Interactive planning process and roles of actors

- The city of Tampere is in a state of change from conventional planning practices towards open and more interactive methods. Heterogeneous groups are said to produce fruitful plans.
- The challenges of interactive city planning are discontinuity and the lack of resources for R&D in city organization, lack of cooperation between competing companies, subjective interests vs. overall benefits, dominant individuals or organizations, and engagement of actors to a long process.
- To implement innovations and manage context, a project owner who has the will and capability to finish the project is needed.
- Current operators have established roles in the planning process and therefore also new areas are planned very much based on old systems. One problem in renewing practices is that operators get into the planning process too late. Another problem is that new technology/service providers have an unclear role in urban planning.
- Resident participation raised two kinds of thoughts: On one hand, citizens are experts in residential area development, participation increases knowledge and acceptability, and heterogeneous groups are creative. On the other hand, participation was found to be frustrating if people resist just on principle.
- Even though there are many actors involved, and city planning needs support from professionals of different fields, the city should still control the process.

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Drivers, Barriers, and Enablers

2. Information production and sharing

- Sufficient information regarding the new system, useful information to all stakeholders (Figure 26), early and skilled presentation of the information, information flow, and decision-maker engagement are needed for a new system breakthrough.

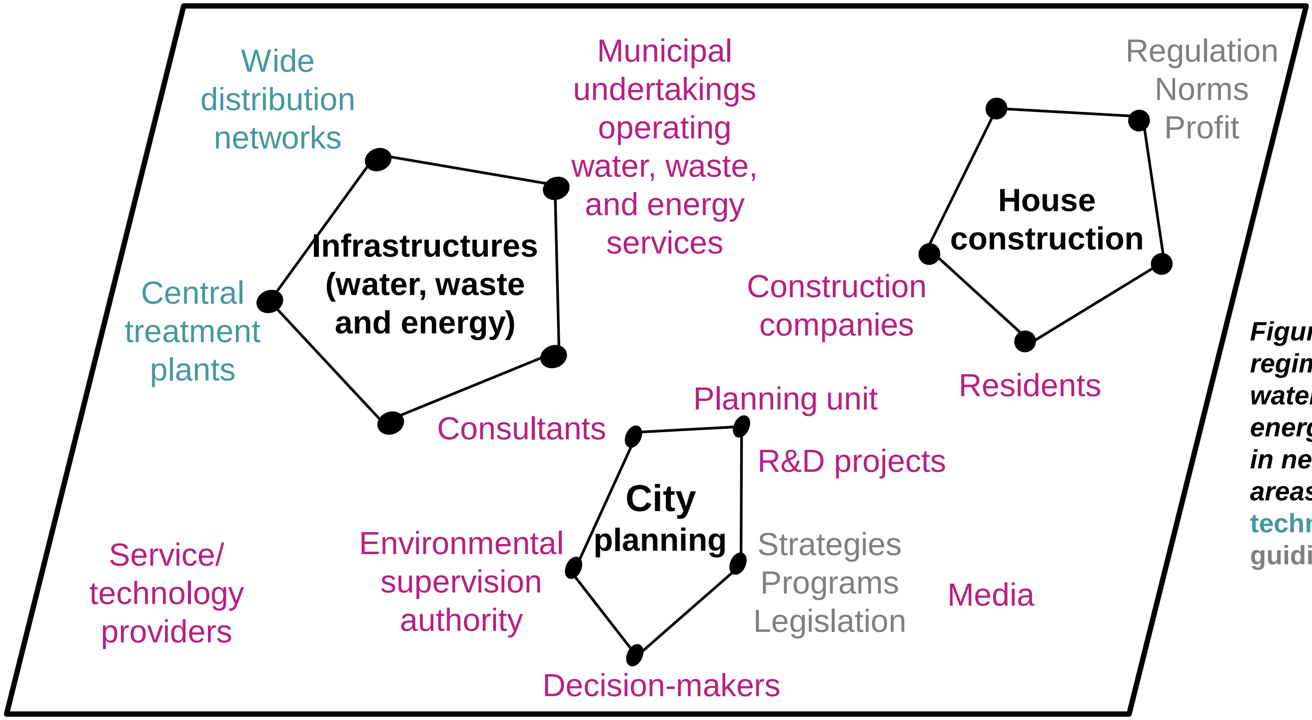

***Figure 26: Current regimes realizing water, waste, and energy infrastructure in new residential areas: actors*, technologies, and guiding principles.**

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Drivers, Barriers, and Enablers

3. Environmental values

- In the sanitation sector, global megatrends, such as growing urban populations that need access to water, sanitation, and energy, are not pushing too hard in Finland.
- Actors in the city of Tampere have interest in enabling green solutions, but sometimes it is difficult to know what to enable. In the planning phase, it is not known what kind of activities are coming to the area or which technologies are starting to fly.
- Environmental values vs economics: On one hand, environmental issues were seen as an expensive extra that competes with cheaper conventional solutions. On the other hand, a better environment was seen to increase the economic value and image of a residential area.
- Environmental values vs acceptability: The studied system was said to include many risks and aspects that people can be against. These issues can be used to complain and slow down new area building, and actual reasons to resist can be either the risk in question or something else.

> *“For city planners, it is easy to promote new solutions, but construction companies bring in economical facts. Sales people sell anything, and some construction companies avoid everything new. Right way is somewhere between.”* (Construction company)

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Drivers, Barriers, and Enablers

"Large share of city financial resources is used to infra, and water infra works well. Therefore changes in it need to be reasoned well." (City of Tampere)

4. Technical development and cost efficiency

- There are plenty of technical solutions for the studied system implementation, but cost efficiency is a big challenge. Small-scale solutions are often challenging to make profitable. However, decentralization and the renewable energy are seen as likely future paths in the energy sector, and technology for small and hybrid systems is being developed. In the sanitation sector, decentralized solutions are widely used in sparsely populated areas, but in urban environments, they are marginal, and service/technology providers don't necessarily see business potential in cities.
- When system cost is calculated, the overall picture needs to be taken into account. Centralization benefits can decrease when some areas are not joining the system. On the other hand, savings, such as the avoidance of long pipes and pumping and light treatment of grey waters, may decrease the overall price of the decentralized system. Also, incentive and output (energy, nutrients) prices affect the profitability of the system.
- New solution testing in pilot projects was highlighted in many interviews. Pilots are said to enable sharing responsibility and risks, raise information, give companies references, facilitate exports, improve technology, test systems, and change legislation. However, upscaling was considered uncertain.

Drivers, Barriers, and Enablers

5. Operations model

- The city of Tampere is in charge of household waste and wastewater, and it has outsourced operations to municipal undertakings. In the studied system, alternative waste (including toilet) collection, transportation, treatment, and output utilization need to be solved.
- New systems open spaces for new roles and actors, and it is necessary to find good partners for each part of the system. Opening value chains is needed to develop new operation and business models.
- Current operators highlight legal responsibilities that bring health/environmental benefits, and reliable and efficient current infrastructure. Increasing the number of actors was seen as challenging.
- Resident-run operations gained critical comments. Professional operators have better resources for continuity, long-term economics, and investments. Some respondents see residents in a bigger role. Biogas plants could be distantly monitored, and resident organizations or energy entrepreneurs could do simple tasks on site. A citizen society can have the vision and power to change current practices.

> *”Especially for infrastructure projects, it is essential to seek solutions creatively and open-mindedly. Otherwise, straightforward implementation according to, e.g., economic realities, can become a barrier.”* (Technology/service provider)

Drivers, Barriers, and Enablers

6. Suitable area

- A natural location for a distributed sanitation system was agreed to be where the city meets countryside. In such locations, synergies could be sought from agriculture.
- Environmentally profiled new residential areas were also seen as potential locations for a distributed system. When an area is more attractive, higher costs and requirements for construction are acceptable. If this kind of area is located near a city center, synergies can be sought from industry (feedstock, energy use, and image) instead of agriculture. In densely built areas near a city, there is also land use competition, where land required for local systems can be challenging to find.
- In Tampere, easy locations are already built. Unlike conventional gravitation sewage, vacuum sewage works uphill, which can be an advantage in a challenging location. In any case, the system needs to be adopted to local conditions.
- It was supposed that, in the beginning, average people do not move to a pilot area. If the system differs from a norm, it requires certain hobbyism, and residents need to be like-minded. On the other hand, it was said that maybe now the time is ripe for change, and people may want to do things in a new way.

> *“In Tampere, there is gas grid, where biogas could be injected. Heat could be fed into smarter district heating network. On the other hand, city is kind of prisoner of existing infra: strong centralized systems can hinder development of new concepts.”* (R&D)

Drivers, Barriers, and Enablers

7. Local benefits

- In a distributed system, it is important to show the circuit where resources are used locally and benefit producers. Such benefits can be environmental, social, and/or economical: e.g., more attractive area with less heavy traffic, lower apartment or public building heating costs, energy supply in emergencies, local biogas vehicle fuel stations, or gas for cooking.
- Overall environmental and economic effects of the distributed system should be evaluated in relation to other systems, namely the dominant central system. In remote locations and small scales, outputs are likely to be more feasible to use locally than to transfer them to the central systems.
- Nutrient recycling from wastewater treatment has not occurred widely in Finland, and barriers include legislation and acceptability. A local system could overcome these barriers, because the nutrient source is known and restricted to household waste. Every case is different, and effects need to be calculated based on certain residential area data.

“Local transportation gas station could work if in traffic node. Motivates new car introduction.” (Current operator)

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Summary of Drivers, Barriers, and Enablers for Alternative System Implementation

Table 19a: Summary of the drivers/barriers/enablers for the studied system implementation in Tampere (continues to the next page)

Theme	Driver (d) / Barrier (b) / Enabler (e)
City planning process	- moving towards open and interactive methods also in Tampere (d) - how to involve residents of the new area? - current operators dominate (b) - new actors’ roles are unclear, and actors get into planning too late (b) - project owner and city control is needed (e)
Information production and sharing	- there are information breaks within city organizations (b) - sufficient information early to different target groups (e) - political will needs to be built (e) - use of communication professionals is recommended (e) - information prevents rumors (e)
Environmental values	- Tampere and other operators promote green values (d) - global megatrends are distant from Tampere sanitation development (b) - difficult to know what (green solutions) to enable (b) - environment vs. economics and acceptability (b)

Summary of drivers, barriers and enablers for alternative system implementation

Table 19b: Summary of the drivers/barriers/enablers for the studied system implementation in Tampere

Theme	Driver (d) / Barrier (b) / Enabler (e)
Technical development	- technology is available (d) - Cost efficiency is a challenge (b) - pilots are demanded, but their upscaling in not systematic (b) - when calculating system cost, the whole picture needs to be included (e) - system maturity (e)
Operations model	- professional partners for each part of the industrial ecosystem (e) - operations and financing solutions require open thinking (e)
Suitable area	- Existing infrastructure (d/b) - Where city and countryside meet (e) - dense urban area with an environmental profile (e) - Challenging profile for gravitation sewage (e)
Local benefits	- Visible local circuit is attractive (e)

Selecting Key Drivers/Barriers and Enablers in Workshops

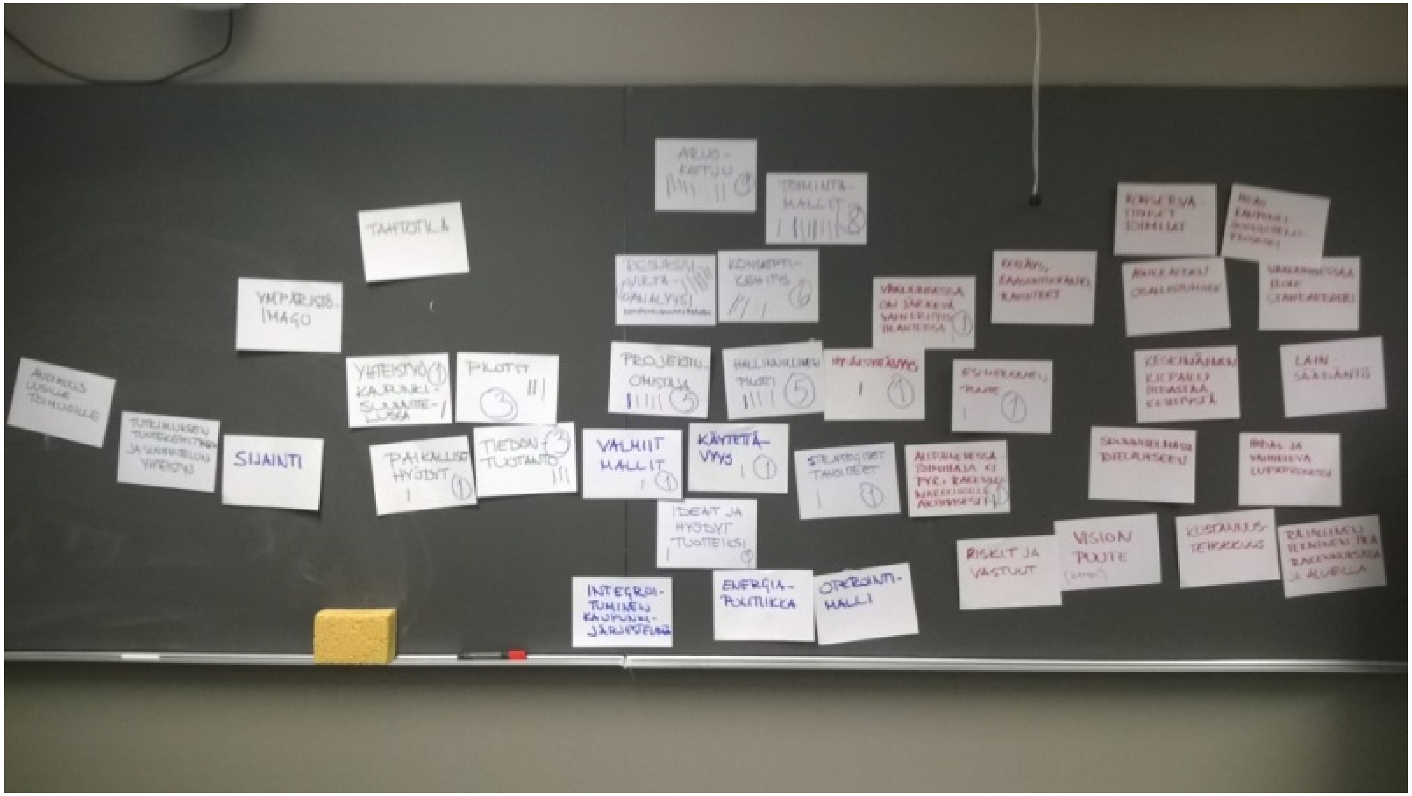

Figure 27: In workshops, drivers (green), barriers (red), and enablers (blue) of alternative solution implementation were discussed and developed. Participants selected the key issues that should be emphasized in this study and further research. Value chain gained nine votes, followed by operation models (8), resource flow analysis (6), concept development (6), management pilot (5), and project owner (5).

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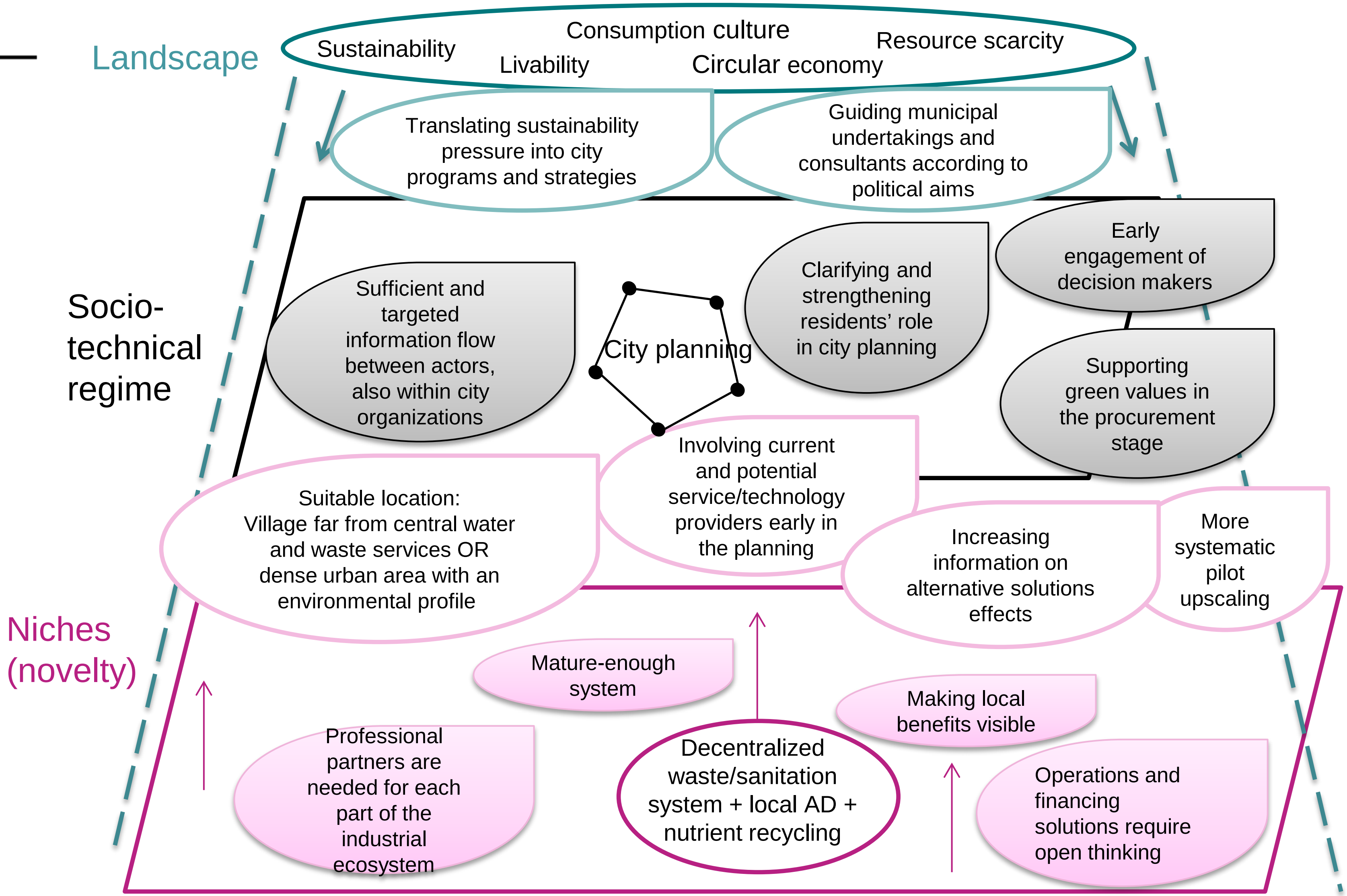
5. How Can We Facilitate Socio-Technical Transition?



Landscape

Sustainability

Consumption culture

Livability

Circular economy

Resource scarcity

Translating sustainability pressure into city programs and strategies

Guiding municipal undertakings and consultants according to political aims

Socio-technical regime

Sufficient and targeted information flow between actors, also within city organizations

City planning

Clarifying and strengthening residents' role in city planning

Early engagement of decision makers

Supporting green values in the procurement stage

Involving current and potential service/technology providers early in the planning

Suitable location: Village far from central water and waste services OR dense urban area with an environmental profile

Increasing information on alternative solutions effects

More systematic pilot upscaling

Niches (novelty)

Mature-enough system

Making local benefits visible

Professional partners are needed for each part of the industrial ecosystem

Decentralized waste/sanitation system + local AD + nutrient recycling

Operations and financing solutions require open thinking

Figure 28: Enablers that should be strengthened in each level (landscape, regime, and niche) and in interaction between the levels when aiming to put a decentralized circular system in a new residential area

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6. Conclusions

At the regime level, we have focused on city planning processes and studied enablers that should be strengthened in order to clear a path for the alternative solution. At the niche level, we have studied characteristics that could make the alternative solution capable of a breakthrough.

Summary of the suggestions

- ☐ The city of Tampere should remain in control and guide the planning process and infrastructure development according to (environmental) policy aims.
- ☐ City planning should be impartial and allow early participation of different actors (operators, potential technology/service providers, residents/commons). Early participation of a wide group of actors could enable dialogue and renew solutions and roles.
- ☐ Interaction and information flow between actors and within city organization, as well as early building of political will, are needed to keep alternative solutions in from the planning table to implementation and to upscale pilots.
- ☐ Studies on overall costs and environmental and social effects, in comparison to current infrastructures, are essential when aiming to create a more sustainable and livable residential area.

The enablers of socio-technical transition are discussed above, but is the decentralized circular system potential part of the infrastructure in the city of Tampere? Critically speaking, some of the results question the ability of the system to improve sustainability and livability. Firstly, a high-profile neighborhood in a virgin area is problematic, because construction on greenfield land is not the desired direction of urban development, and a livable (Haan et al., 2014) area should be accessible to a wider socio-economic group. Secondly, technical maturity and acceptability of the decentralized circular system are doubtful. Finally, possible negative environmental effects need to be considered if the decentralized circular system is implemented

7. Next Steps

This study focused on one niche-level innovation and how it could unbalance incumbent regimes in Tampere. However, the results elicit still wider questions of socio-technical transition in infrastructure sectors. Any niche-level innovation would have similar struggles to get into urban land-use planning and to be actually implemented. Some of the successful niche-innovation characteristics hold to any niche-level innovation (e.g., technical maturity, visible local benefits, and competent partners for each part of the industrial ecosystem), while other characteristics are more case-specific (e.g., suitable location and acceptability). Further research should include residents' role in sustainability transition within infrastructure sectors, homes as an interface to infrastructure systems, information flow in land-use planning, and pilot upscaling.

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