Journal of Cleaner Production 135 (2016) 1065–1084

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Designing integrated local production systems: A study on the food-energy-water nexus

Melissa Yuling Leung Pah Hang [a], Elias Martinez-Hernandez [b], Matthew Leach [a], Aidong Yang [b,*]

[a] Centre for Environmental Strategy, University of Surrey, Guildford, GU2 7XH, UK
[b] Department of Engineering Science, University of Oxford, Oxford, OX1 3PJ, UK

ARTICLE INFO

Article history:
Received 19 January 2016
Received in revised form
30 June 2016
Accepted 30 June 2016
Available online 5 July 2016

Keywords:
Local production system
Mathematical optimisation
Resource consumption
Exergy
Food-energy-water nexus

ABSTRACT

Centralised production of essential products and services based on fossil fuels and large scale distribution infrastructures has contributed to a plethora of issues such as deterioration of ecosystems, social-economic injustice and depletion of resources. The establishment of local production systems that deliver various products for local consumption (e.g. food, energy and water) by making the best use of locally available renewable resources can potentially alleviate unsustainable resource consumption. The main objective of this work is to develop process systems engineering tools combined with the concept of resource accounting using exergy for the design of such local production systems. A general design framework comprising an optional preliminary design stage followed by a simultaneous design stage based on mathematical optimisation is proposed. The preliminary design stage considers each supply subsystem individually and allows insights into the potential interactions between them. The simultaneous design stage yields an optimal design of the local production system and has the capacity to include all design integration possibilities between the subsystems and generate a truly integrated design solution. The proposed methodology, which reflects generalised principles for designing local production systems, has been illustrated through a case study on the integrated design of the food-energy-water nexus for a designated eco-town in UK. It demonstrates the advantages of an integrated design of a system making use of local resources to meet its demands over a system relying on centralised supplies and a design without considering integration opportunities between subsystems.

1. Introduction

With the advent of industrialisation, the supply of energy and materials to meet human needs has been driven primarily by centralised production, harnessing economies of scale, based on fossil fuels and large scale distribution infrastructures. However, continuation of this mode of production coupled with growing population has led to a range of issues such as climate change, energy supply insecurity, deterioration of ecosystems and depletion of resources. Local production systems have been regarded as one possible pathway towards sustainability (Royal Academy of Engineering, 2011). Though the challenges are global, they have local impacts and may affect each local system differently. This calls for the engineering of human-made systems with a focus on the rational use of locally available resources. Such systems require new design tools to allow decision makers to explore the roles of local details such as the significance of local resource use and the opportunities for interactions between co-located subsystems.

A local production system is defined as a network of heterogeneous processes, integrated in a synergistic manner to achieve a high degree of resource efficiency, potentially leading to improved economic viability while preserving the ecosystem (Martinez-Hernandez et al., 2016). It considers all types of production processes that can occur at a local scale for the production of products (e.g. food) and/or services (e.g. heat) to satisfy local demands. While these processes differ in technical natures, they share the following characteristics desirable from sustainability perspectives; it is precisely this set of common characteristics that is to be explored by this work. First of all, these systems offer the possibility to use renewable resources which can be captured or produced locally to meet demands of the local population. They also have the

* Corresponding author.
E-mail address: aidong.yang@eng.ox.ac.uk (A. Yang).

http://dx.doi.org/10.1016/j.jclepro.2016.06.194
0959-6526/

Nomenclature

Sets

$a \in A$ Water sources
$ag \in AG$ Agricultural commodities
$b \in B$ Water sinks
$b' \in B'$ Regenerator water sinks
$c \in C$ Crops
$d \in D$ Food types
$i \in I$ Nutrient sources
$i' \in I'$ Imported nutrient sources
$i'' \in I''$ Locally produced nutrient sources
$j \in J$ Food sinks
$l \in L$ Livestock
$o \in O$ Operating flows
$r \in R$ Energy raw material
$s \in S$ Seasons
$x \in X$ Energy sources
$y \in Y$ Energy sinks

Parameters

$cb_{c,d}$ Conversion factor from crop *c* to food *d*
$cf_{l,d}$ Conversion factor from livestock *l* to food *d*
cod_b Maximum allowable COD of water sink *b*, g COD/kg
$e_{o,j}$ Specific cumulative exergy of operating flows *o* to nutrient sink *j*, MJ/kg or MJ/MJ
e_r Specific cumulative exergy of raw material *r* for energy production, MJ/kg
e^{cw} Specific cumulative exergy of chemicals per unit wastewater, MJ/kg
e^{elw} Specific cumulative exergy of electricity per unit wastewater, MJ/kg
e^{hew} Specific cumulative exergy of heat per unit wastewater, MJ/kg
e^{ie} Specific cumulative exergy of imported energy, MJ/MJ
e^{iel} Specific cumulative exergy of total imported flows for producing electricity, MJ/kg
e^{ihe} Specific cumulative exergy of total imported flows for producing heat, MJ/kg
e_x^{el} Specific cumulative exergy for producing electricity from source *x*, MJ/kg
e_x^{he} Specific cumulative exergy for producing heat from source *x*, MJ/kg
e_d^{imp} Specific cumulative exergy of imported food *d*, MJ/kg
$e_{i',j}^{imp}$ Specific cumulative exergy of imported nutrient flows *i'* to nutrient sink *j*, MJ/kg
$E_{y,s}^{dem}$ Electricity demand at sink *y* per season *s*, GJ
ELD_d Electricity demand per unit food *d*, MJ/kg
$F_{d,s}^{dem}$ Demand of food *d* in season *s*, t
FC Nominal size of storage facility, t
$H_{i''}$ Harvest recovery rate of locally produced nutrient sources *i''*
$H_{y,s}^{dem}$ Heat demand at sink *y* per season *s*, GJ
H^{Max} Maximum heat load in waste heat, GJ
HED_d Heat demand per unit food *d*, MJ/kg
$L_{r,x}$ Land use per unit raw material *r* from source *x*, ha/MJ
L^{agri} Total amount of agricultural land available, ha
L^{en} Land available for energy production, ha
$M_{r,s}^{Av}$ Availability of raw material *r* in season *s*, MJ
$N_{j,s}^{dem}$ Demand of nutrient sink *j* in season *s*, kg
$nc_{i''}$ Nutrient content of locally produced nutrient sources *i''*, kg N
$y_{c,s}$ Yield of crop *c* per season *s*
y_l Yield of livestock *l*
RA_{ag} Amount of residues or manure per unit of agricultural commodity, kg/kg
Ref COD removal efficiency of treatment plant, %
RW_s Amount of rainwater collected in season *s*, t
SED^{WA} Electricity demand for treating unit wastewater, MJ/kg
SHD^{WA} Heat demand for treating unit wastewater, MJ/kg
SL Number of years of service life of storage facility, y
t Time period over which heat is transferred, y
$T_{x'}^{in}$ Inlet temperature of heat source *x'* before heat exchange, °C
$T_{x'}^{out}$ Outlet temperature of heat source *x'* after heat exchange, °C
T_y^{in} Temperature of heat sink *y* before heat exchange, °C
T_y^{out} Temperature of heat sink *y* after heat exchange, °C
TD Minimum temperature difference, °C
TE Specific cumulative exergy of operating resources per unit accumulated crop, MJ/kg
UTD Upper bound for temperature difference, °C
$W_{b,s}^{dem}$ Water demand of sink *b* in season *s*, t
WC_d Amount of water required for agriculture per unit food *d*, kg/kg
WE Amount of water required per energy produced, kg/MJ
WEG Amount of wastewater generated per energy produced, kg/MJ
WGP_d Amount of wastewater generated per unit food *d*, kg/kg
WP_d Amount of water required for industrial processing per unit food *d*, kg/kg
$\eta_{x,r}^{el}$ Electrical efficiency of source *x* for raw material *r*
$\eta_{x,r}^{he}$ Heat efficiency of source *x* for raw material *r*

Variables

$A_{ag,s}$ Amount of agricultural commodity *ag* produced during season *s*, t
$A_{c,s}$ Amount of crop *c* locally produced in season *s*, t
$AC_{c,s}$ Amount of crop *c* accumulated at season *s*, t
$AC_{c,s-1}$ Amount of crop *c* accumulated from season *s*−1, t
AR_{s-1} Amount of rainwater accumulated from season *s*−1, t
AW_s Amount of rainwater available for consumption in season *s*, t
CA_c Capital exergy resources for storage of crop *c*, GJ
CA^{rw} Total capital exergy resources for rainwater storage, GJ
$cod_{b',s}$ COD of treated wastewater from treatment plant sink *b'* in season *s*, g COD/kg
$CP_{x',s}$ Heat capacity flow rate of source *x'* for season *s*, GJ/season
$CS_{y,s}$ Heat capacity flow rate of sink *y* for season *s*, GJ/season
$E_{x,grid,s}$ Amount of electricity from source *x* exported to grid in season *s*, GJ
$E_{x,y,s}$ Amount of electricity from source *x* to sink *y* in season *s*, GJ
ELD_s^{FD} Total electricity demand of food processes in season *s*, GJ
ELD_s^{WA} Total electricity demand of water processes in season *s*, GJ
$F_{d,s}^{crop}$ Amount of locally produced food *d* from crop in season *s*, t
$F_{d,s}^{imp}$ Amount of imported food *d* in season *s*, t
$F_{d,s}^{live}$ Amount of locally produced food *d* from livestock in season *s*, t
$F_{d,s}^{local}$ Amount of locally produced food *d* in season *s*, t
$H_{x,y,s}$ Amount of heat from source *x* to sink *y* in season *s*, GJ