npj | clean energy

https://doi.org/10.1038/s44406-026-00021-z

Mobilizing sustainable energy – the importance of rural regions, small units and energy villages

Nebiyu Girgibo[1] ✉, Pekka Peura[1] & Ari Haapanen[2]

Small rural regions, termed energy villages, are potentially self-sufficient, due to the renewable energy sources harvestable nearby, and most such villages would be able to produce further energy or raw materials, energy for sale outside their region. In many areas, bioenergy would suffice to cover the demand for all energy (electricity, heating, transport, agriculture etc.), and overall in all research areas, bioenergy potential corresponds to some 1/3 of the consumption of energy. Wind and solar power could thus make regions over-productive. The same applies to larger regions, consisting of multiple small villages. An increasing number, rural areas are capable in covering the energy demand cities within the region, including the industries there. The economic potential is vast. The values used here were estimated before the Russian–Ukrainian war, therefore, is not possible currently to provide an accurate current value, other than to estimate that prices and the entire economic value of energy will increase. Also, and as this is not a technical planning document, it has not been possible to analyze more precisely single separate or systemic regional solutions. Our paper presents and discusses the logical framework within which rural regions are crucial in the process of sustainable energy transition.

Sustainable energy transition (SET) has been high on the energy sector's agenda throughout this century. The transition entails increased and widespread use of renewable energy sources (RESs) in the production of energy (ref. 1 including review). RESs, together with the rational use of energy (RUE; energy saving and energy efficiency), are the main constituents of sustainable energy (SE, e.g.,[1–4]). Today, there are several positive drivers for SE. It has been acknowledged, for instance, that there is realistic potential for RESs to satisfy today's energy demand even globally (for a review and references[1,5]). Also, RES business profitability, and its benefits beyond business, specifically the "regional value added" (monetary aspects, reduction of costs, increase of purchasing power, new employment, tax income, social, ecological and ethical aspects, improved vitality[6,7]), can be significant. The social acceptance of RESs, observed since the early 1980s[8], has enabled the SET to become a comprehensive global movement. Alongside the SET, technical evolution is accelerating with new solutions constantly emerging and being implemented. "There is a consensus that the energy system will need to change, but … a lot of uncertainty … [of] … how"[9].

Like most other major societal transitions, the SET has also met with big challenges. The diffusion of RES-based energy management systems means a total replacement of fossil fuels by RE. This will require new technologies and institutional frameworks (e.g.,[10–15]). The prevailing actors, with massive resources and networks, have often prevented developments that do not support their business[16] and RES solutions are fighting against existing structures. Today, this is changing as utilities begin to accept RES. However, the rules of the game have "…historically been developed to support the incumbent centralized power system"[17]. For new solutions to fully manifest, there still is a need to develop value chains in order to make production efficient and to create markets, i.e., a system of supply and demand. However, institutional issues and other barriers slow the process; these barriers are non-technical challenges, rather than technical issues[18]. The diffusion of separate innovations, especially the systemic level of transition, and the shift towards these structures, different from the prevailing centralized system, will be a long evolutionary societal process, and the involvement of all stakeholders will be necessary. It is crucial that the main principles of SE are followed, and, in particular, that the solutions are sustainable (cf.[1,7,19–22]).

The importance of small units and regions has become more obvious, as has recently been acknowledged in the SET conversation: rural regions will be among the main focuses when implementing SE and the SET. This will have a significant impact on rural regions globally and may even result in a disruptive change in the societal role of rural regions. The rural energy transition has remained rather unexplored, but its potential and logical framework are clear: "urban energy transitions are simply impossible without rural energy transitions"[23]. To make the implementation of RES-based solutions credible and convincing, it is essential to consider the

---

[1]Vaasa Energy Business Innovation Centre (VEBIC), University of Vaasa, Vaasa, Finland. [2]Gas1 Oy, Lahti, Finland. ✉e-mail: nebiyu.girgibo@uwasa.fi

strategy, organization and concepts creatively. As the energy content per mass unit is much smaller in RES than in fossil fuels, the transition will clearly affect and essentially prevent global or long-range logistics. This will result in more regional, even local, praxes utilizing the RES, both in terms of producing and consuming energy, and "…energy transition will bring about a more decentralized global energy system"[24]. Smaller-scale production units, in contrast against today's highly centralized plants, will become more common, as well as a distributed strategy in energy management. The production units can still be relatively large and "regionally centralized", although they are "distributed", i.e., producing energy for proximal distribution networks and close-range delivery[4]. Such a configuration also offers huge potential to establish profitable production units for all energy vectors—electricity, heating, transport fuel, agriculture, industries—which contribute to improving regional economies and their vitality, especially in rural regions (Table 1).

This scenario means a two-way benefit for rural regions:

- Because most RESs grow, are located, or can be harvested in large countryside areas, rural regions will be the focus in terms of SET. This may lead to a significant shift of the societal role of rural regions.
- The potential regional economic and employment impacts are among the most powerful drivers for SE. For instance, it is repeatedly claimed that RESs generate more jobs than conventional energy (e.g.,[7,25]). RESs, especially existing but presently unused resources, can play an important role in vitalizing regional and particularly rural economies.

Money currently spent on importing fossil energy could be kept circulating in the regional economy. Such spending can reach €5000 per capita per year, so, in a region with just over 2,00,000 inhabitants, this would total €1Bn every year (in Finland[7]). These first results suggest that the regional economic impact would increase considerably were the region self-sufficient in raw materials, including intermediates. The literature on the socio-economic impacts of SE, although not yet very extensive, mainly concentrates on costs and employment, the methods for analyzing employment within certain branches or separate technologies and their value chains, and includes jobs created during the construction phase, the operation and maintenance of the studied plants (for reviews, see[9,26,27]) or low-carbon technologies, including RES[28].

Effecting the transition is much more than a merely technical operation. Besides technologies, the main dimensions include the macroeconomy, the regional economy, general rules and regulations, social acceptance, societal structuring processes, and environmental drivers, etc., all of which point to the need to develop implementation procedures. The literature agrees that the "implementation processes of renewable energy require "strong" ecological modernization" and, above all, "(…) trust": all relevant stakeholders must be committed to "open democratic decision-making, participation and involvement, and incorporation of multiple views". The transition towards RES "requires (…) innovative institutional frames" and societal innovations (quotations[14]).

Due to the complexity and need for long-term societal structuring in conjunction with technical and economical evolution and the diffusion of innovations within the transition process, it is essential to pay attention to the implementation processes in terms of promoting this complex, society-wide reconfiguration—not only by committing citizens and consumers, but also by creating whole communities and entities capable of functioning as units in the energy sector. This paper discusses the rural SET in general, introducing the importance of the rural context, and, in terms of implementation, it examines the energy village (EV) concept. EV is a general concept that describes smaller and predominantly rural regions which aim at or have the potential to be self-sufficient in their production of energy, including the procedures from idea to implementation.

More specifically, we aim to answer the following research questions:

Research question 1: What is the SE self-sufficiency potential in terms of RES from within the own area in small regional units, referred to here as EVs, and in larger regions, which consist of EVs?

Research question 2: What is the economic potential of SE in rural regions?

In this paper, the Section "Results" defines the EV concept, the Section "Discussions" describes the research areas, methods, research gaps, approach, and limitations, and in the Section "Methods", we present the results. Chapter 5 discusses and concludes the research.

Results

Consumption of energy in the research areas

The results have been collated in Tables 2–5. The research sites altogether consume nearly 12 TWh/annum of electricity, heating energy, and energy for transport, agriculture, and other purposes, of which some 73% is consumed in Ostrobothnia, ca. 20% in the city of Vaasa alone, and a little over a third among the cities of Vaasa, Pietarsaari, and Kaskinen. The variation in energy consumption is mainly within the range of ca. 30–70 MWh/a per capita. The exceptional peaks in average consumption (per capita) are caused by a large wood refining factory in Kaskinen, the considerable greenhouse concentration in Närpiö, and the large mining companies active in Sodankylä, all accompanied by relatively small populations (Table 1). The total consumption of electricity, heating energy, and energy for other purposes across the research sites is 4.2 (35%), 3.4 (29%), and 4.3 (36%) TWh/a, respectively. The village research sites consume around 605 GWh/a of energy. The share of their electricity consumption in relation to the total consumption is significantly smaller than across all sites, some 20% of the total consumption, while heating corresponds to ca. 33%, and transport and other purposes amount to as much as 46%. In the case of the municipalities (including the small rural cities of Kristiinankaupunki, Uusikaarlepyy, and Kauhava, excluding Vaasa and Pietarsaari), the shares are 33, 26, and 41%, respectively, and the total consumption is around 8 TWh/a. Correspondingly, the share of electricity is clearly the highest in Kaskinen (85%), Sodankylä (66%), and Pietarsaari (53%).

The share of energy used for transport and agriculture is substantial in the rural sites, varying mainly within the range of 35–57% of the total consumption of energy. However, the share is small in Kaskinen (3.4%), Närpiö (23%), Sodankylä (ca. 20%), and in the cities of Vaasa (ca. 34%) and Pietarsaari (23%). The rural sites consume more heating energy than electricity, but, depending on the economic structure and, for instance, the presence of large energy-intensive enterprises, some of these sites use significantly more electricity. The potential RE here includes bioenergy and wind power. Bioenergy consists of the materials available for biogas production and combustion, which are listed separately (Table 3). Wind power includes both the turbines already erected and the planned wind parks and smaller production units. The total RES potential within the research sites is ca. 23 TWh/a. Nearly 81% of this is wind power (1.8 TWh/a of existing turbines and 16.9 TWh/a planned). Bioenergy potential is 3.75 TWh/a, slightly more than 18% of the total potential.

The main component of the bioenergy potential is that of combustible materials (2.8 TWh/a). while the biogas potential is just below 1 TWh/a. There are large wind parks planned for the villages of Siipyy, Tiukka, and Dagsmark in Kristiinankaupunki, and in the villages of Jepua and Pensala in Uusikaarlepyy. Moreover, a great deal of wind power is planned for all regions and for most municipalities within the research areas, while some villages (Kallträsk, Härkmeri, Lapväärti, Komossa, Alahärmä, Sassali) and municipalities (Pietarsaari, Kruunupyy, Kaustinen, Sodankylä) have neither existing nor planned wind power. The main element of bioenergy comes from forestry, consisting mostly of logging residues and thinnings from younger forests. The biogas and straw potential are typical by-products from agriculture, indicating the volume of cultivation residues, predominantly from rural areas, some of which are also located within the borders of cities. The Ostrobothnian counties are known for their strong agricultural tradition, the by-products of which increase their biogas and straw potential to a level that equals the forest energy potential, while in Lapland, forestry produces the greatest energy potential by far. In the cities, the main source of biogas potential is wastewater sludge and organic waste separated at source.

Table 1 | Characteristics of the research areas: population (1000 inhabitants in 2020), land area (km^2), economic structure, and unemployment (%, in 2019; source[61])

Region Municipality *Village*	Population 1000 inhabitants	Land area km^2	Primary production %	Secondary production %	Services%	Unemploy-ment %
Vaasa	67.6	364.7	0.4	27.3	71.4	8.5
Vähäkyrö	5.36	215.7				
Kristiinankaupunki	6.49	683.3	10.7	16.1	71.1	4.9
Dagsmark	0.41	69.5				
Härkmeri	0.37	114.4				
Kallträsk	0.059	19.7				
Center	2.83	40.8				
Lapväärtti	1.72	138.6				
Metsälä – Kallträsk	0.20	72.4				
Siipyy	0.15	79.7				
Skaftung	0.23	41.4				
Tiukka	0.51	75.2				
Vöyri	6.38	782.1	13.9	31.4	53.0	3.8
Komossa	0.22	72.8				
Uusikaarlepyy	7.54	732.7	14.7	38.8	45.1	3.9
Jepua	0.94	155.7				
Pensala	0.34	47.6				
Laihia	7.94	505.2	8.1	21.8	68.1	6.9
Korsnäs	2.06	236.0	20.3	14.0	62.0	6.4
Närpiö	9.59	977.8	23.2	23.8	51.5	3.9
Maalahti	5.50	521.8	10.0	28.2	59.7	5.6
Luoto	5.63	142.5	2.7	40.9	55.1	2.1
Pietarsaari	19.1	88.5	1.0	38.8	59.2	7.6
Pedersöre	11.2	794.3	10.4	45.1	43.3	2.9
Kruunupyy	6.44	712.9	12.2	40.8	45.4	3.9
Mustasaari	19.5	849.2	5.6	27.6	64.4	4.6
Kaskinen	1.28	10.6	1.9	39.4	56.8	6.5
Ostrobothnia	179.3	7401.4	5.0	30.4	63.3	6.3
without Vaasa	114.0					
Kauhava	15.3	1313.9	11.8	30.5	56.2	8.0
Alahärmä	2.33	102.4				
Teuva	5.04	554.7	15.3	22.8	59.9	7.0
Isojoki	1.94	642.4	21.9	24.0	51.7	5.3
Perho	2.70	747.9	16.7	28.6	52.9	9.0
Perho center	1.24	290.7				
Veteli	3.11	502.1	21.5	22.0	54.7	6.2
Toholampi	3.04	609.0	21.1	25.2	51.6	6.6
Lestijärvi	0.72	480.0	36.5	12.3	48.5	10.2
Kaustinen	4.26	353.9	14.8	21.0	62.3	5.8
Halsua	1.11	413.0	27.8	23.0	47.0	8.8
Kaustinen Region	14.9					
Sodankylä	8.31	11693	6.4	27.1	65.5	7.4
Sassali	0.053	82.5				
Salla	3.40	5729.8	13.3	6.4	79.1	15.8
Posio	6.25	3039.7	20.9	13.4	64.0	16.7
Tervola	6.34	1559.7	15.3	22.8	59.9	12.6
FINLAND	5533.8	303948	2.7	20.7	75.1	9.8

Table 2 | Consumption of energy in the research areas: electricity, heating, transport, and agriculture (GWh/annum) and per capita (MWh/annum)

Region **Municipality** ***Village***	**Electricity**	**Heating**	**Transport, Agriculture**	**TOTAL**	**Per capita**
Vaasa	542	1056	835	**2432**	36
Vähäkyrö	38	44	66	**148**	28
Kristiinankaupunki	62	101	169	**332**	51
Dagsmark	3.9	8.9	11	**23**	58
Härkmeri	3.5	7.4	9.6	**21**	56
Kallträsk	0.6	1.3	1.5	**3.4**	58
Center	27	34	74	**135**	48
Lapväärti	16	28	45	**89**	52
Metsälä – Kallträsk	1.9	4.3	5.3	**12**	57
Siipyy	1.4	5.1	3.8	**10**	70
Skaftung	2.2	5.7	6.0	**14**	60
Tiukka	4.9	8.3	13	**26**	52
Vöyri	65	112	162	**338**	53
Komossa	2.2	4.6	5.5	**12**	57
Uusikaarlepyy	108	116	174	**398**	53
Jepua	13	17	22	**52**	55
Pensala	4.8	6.3	7.7	**19**	56
Laihia	62	76	152	**290**	36
Korsnäs	35	31	48	**114**	55
Närpiö	630	164	238	**1032**	108
Maalahti	64	67	125	**256**	47
Luoto	31	35	81	**147**	26
Pietarsaari	616	273	272	**1161**	61
Pedersöre	118	139	236	**493**	44
Kruunupyy	116	91	144	**351**	54
Mustasaari	175	201	382	**758**	39
Kaskinen	529	69	21	**619**	483
Ostrobothnia	3153	2500	3039	**8698**	
without Vaasa	2649	1488	2270	**6408**	
Kauhava	168	290	385	**843**	55
Alahärmä	26	42	58	**126**	54
Teuva	57	92	112	**262**	52
Isojoki	29	37	56	**123**	63
Perho	12.0	33	59	**104**	39
Perho center	5.5	14	27	**47**	38
Veteli	30	54	69	**153**	49
Toholampi	40	48	65	**153**	50
Lestijärvi	10	13	16	**38**	54
Kaustinen	52	106	95	**253**	59
Halsua	12	16	27	**55**	50
Kaustinen Region	156	238	330	**725**	
Sodankylä	540	108	168	**816**	98
Sassali	0.8	0.9	1.1	**2.7**	51
Salla	38	49	71	**158**	47
Posio	39	44	71	**154**	50
Tervola	41	42	68	**151**	52

Table 3 | The potential of RE (GWh/annum) in the research areas

Region **Municipality** ***Village***	**Biogas**	**Forest**	**Straw**	**Waste**	**Wind existing**	**Wind planned**	**TOTAL**
Vaasa	153	35	29	65	135	40	**461**
Vähäkyrö	15	12	23	5.1	127	40	**226**
Kristiinankaupunki	24	79	14	6.2	286	3604	**4012**
Dagsmark	1.9	9.8	2.0	0.4	0	694	**708**
Härkmeri	1.6	5.9	1.0	0.4	0	0	**8.8**
Kallträsk	0.5	3.5	0.1	0.06	0	0	**4.2**
Center	6.9	12	0.9	2.7	7.2	40	**70**
Lapväärti	5.7	14	4.2	1.6	0	0	**26**
Metsälä – Kallträsk	1.7	13	1.1	0.2	0	277	**293**
Siipyy	1.4	12	0.3	0.1	0	1526	**1540**
Skaftung	1.1	5.8	0.3	0.2	0	156	**163**
Tiukka	2.3	9.3	3.2	0.5	0	1188	**1203**
Vöyri	46	86	44	6.1	0	158	**340**
Komossa	3.8	6.2	3.7	0.2	0	0	**14**
Uusikaarlepyy	90	84	32	7.2	79	624	**916**
Jepua	42	14	8.0	0.9	16.8	624	**706**
Pensala	3.8	4.7	5.6	0.3	4.8	272	**291**
Laihia	22	59	33	7.6	0	216	**338**
Korsnäs	7.7	29	3.7	2.0	0	612	**654**
Närpiö	38	115	57	9.2	463	1778	**2459**
Maalahti	22	59	21	5.3	127	469	**702**
Luoto	14	16	0.5	5.4	2.4	0	**38**
Pietarsaari	43	8.4	0.7	18	0	0	**70**
Pedersöre	65	91	23	11	0	1304	**1494**
Kruunupyy	54	81	15	6.2	0	0	**155**
Mustasaari	49	107	38	19	158	108	**479**
Kaskinen	2.6	1.0	0	1.2	0	0	**4.8**
Ostrobothnia	629	849	309	169	1249	8913	**12123**
without Vaasa	476	813	280	104	1115	8873	**11661**
Kauhava	80	97	83	15	9.6	137	**421**
Alahärmä	8.6	7.2	8.0	2.2	0	0	**26**
Teuva	24	69	25	4.8	20	323	**466**
Isojoki	12	63	7.5	1.9	141	1325	**1551**
Perho	21	53	4.5	2.6	65	749	**894**
Perho center	7.5	18.8	0.9	1.2	65	70	**163**
Veteli	28	35	7.0	3.0	0	108	**185**
Toholampi	31	52	11	2.9	0	1248	**1345**
Lestijärvi	6.3	38	1.5	0.7	0	1133	**1180**
Kaustinen	31	32	7.2	4.1	0	0	**76**
Halsua	13	25	4.5	1.1	0	1056	**1107**
Kaustinen Region	130	236	36	14	65	4294	**4786**
Sodankylä	23	329	0	8.0	187	0	**914**
Sassali	0.2	3.5	0	0.05	0	0	**3.7**
Salla	11	223	0.02	3.3	0	767	**314**
Posio	15	156	0.03	2.9	55	264	**995**
Tervola	18	95	1.1	2.8	72	864	**1554**

Table 4 | Energy balance (consumption, RES potential, consumption–potential, GWh/a; balance and RES potential without wind power, %) in the research areas

Region **Municipality** ***Village***	**Consumption GWh/annum**	**RES potential GWh/annum**	**BALANCE GWh/annum**	**BALANCE %**	**RES–Wind %**
Vaasa	2433	461	−1971	19	12
Vähäkyrö	148	226	79	153	37
Kristiinankaupunki	332.3	4012	3679	1207	37
Dagsmark	23	708	685	3078	61
Härkmeri	21	8.8	−12	42	42
Kallträsk	3.4	4.2	0.8	124	122
Center	134.8	70	−64	52	17
Lapväärti	89.2	26	−63	29	29
Metsälä – Kallträsk	12	293	281	2442	133
Siipyy	10	1540	1529	15,400	138
Skaftung	14	163	149	1164	53
Tiukka	26.4	1203	1177	4557	58
Vöyri	338	340	1.9	101	54
Komossa	12	14	1.6	117	116
Uusikaarlepyy	398.0	916	518	230	54
Jepua	52	706	654	1358	125
Pensala	19	291	273	1532	76
Laihia	290	338	48	117	42
Korsnäs	114	654	540	574	37
Närpiö	1032	2459	1427	238	21
Maalahti	256	702	446	274	42
Luoto	147	38	−109	26	24
Pietarsaari	1161	70	−1091	6	6
Pedersöre	493	1494	1000	303	39
Kruunupyy	351	155	−196	44	45
Mustasaari	758	479	−278	63	28
Kaskinen	619	4.8	−614	1	1
Ostrobothnia	8692	12123	3431	139	23
without Vaasa	6408	11661	5402	182	26
Kauhava	843	421	−422	50	33
Alahärmä	126	26	−100	21	21
Teuva	262	466	204	204	47
Isojoki	123	1551	1428	1261	69
Perho	104	894	790	860	78
Perho center	47	163	116	347	60
Veteli	153	185	32	121	48
Toholampi	153	1345	1192	879	63
Lestijärvi	38	1180	1141	3105	122
Kaustinen	253	76	-177	30	29
Halsua	55	1107	1051	2013	79
Kaustinen Region	725	4786	4062	660	57
Sodankylä	816	914	98	112	44
Sassali	2.7	3.7	1.0	137	139
Salla	158	314	155	199	150
Posio	154	995	841	646	113
Tervola	151	1554	1403	1029	77

Table 5 | Costs of energy in the research areas (millions of euros, M€/annum) and per capita (Euros; €/annum)

Region Municipality *Village*	Electricity	Heating	Transport, Agriculture	TOTAL	Per capita
Vaasa	28.2	37.0	189	**254**	3758
Vähäkyrö	2.0	1.6	18.2	**21.7**	4049
Kristiinankaupunki	3.2	3.5	42.3	**49.1**	7568
Dagsmark	0.20	0.31	2.9	**3.4**	8434
Härkmeri	0.18	0.26	2.6	**3.0**	8227
Kallträsk	0.03	0.05	0.42	**0.50**	8459
Center	1.4	1.2	17.4	**19.9**	7050
Lapväärti	0.85	1.0	11.3	**13.1**	7637
Metsälä – Kallträsk	0.10	0.15	1.5	**1.7**	8397
Siipyy	0.07	0.18	1.3	**1.5**	10,186
Skaftung	0.11	0.20	1.7	**2.0**	8805
Tiukka	0.25	0.29	3.4	**3.9**	7669
Vöyri	3.4	3.9	42.7	**49.9**	7830
Komossa	0.12	0.16	1.6	**1.8**	8486
Uusikaarlepyy	5.6	4.06	43.5	**53.2**	7056
Jepua	0.70	0.59	5.6	**6.9**	7379
Pensala	0.25	0.22	2.0	**2.5**	7451
Laihia	3.2	2.7	36.0	**41.9**	5269
Korsnäs	1.8	1.1	9.2	**12.1**	5874
Närpiö	32.8	5.8	60.7	**99.2**	10,349
Maalahti	3.3	2.4	30.7	**36.4**	6618
Luoto	1.6	1.2	19.8	**22.6**	4018
Pietarsaari	32.0	9.6	70.2	**111.8**	5853
Pedersöre	6.1	4.9	59.2	**70.2**	6286
Kruunupyy	6.0	3.2	36.2	**45.4**	7055
Mustasaari	9.1	7.0	93.4	**109.4**	5602
Kaskinen	27.5	2.4	4.6	**34.5**	26,945
Ostrobothnia	164.0	87.5	737.4	**988.9**	5515
without Vaasa	137.8	52.1	566.5	**756.4**	6635
Kauhava	8.7	10.2	100.5	**119.4**	7793
Alahärmä	1.3	1.5	15.3	**18.1**	7789
Teuva	3.0	3.2	30.0	**36.2**	7184
Isojoki	1.5	1.3	12.9	**15.7**	8081
Perho	0.62	1.2	11.4	**13.2**	4909
Perho center	0.29	0.49	6.0	**6.7**	5435
Veteli	1.5	1.9	18.0	**21.5**	6897
Toholampi	2.1	1.7	15.5	**19.3**	6361
Lestijärvi	0.52	0.4	3.6	**4.6**	6362
Kaustinen	2.7	3.7	24.9	**31.3**	7348
Halsua	0.62	0.57	6.1	**7.3**	6575
Kaustinen Region	8.1	8.3	79.6	**97.2**	6523
Sodankylä	28.1	3.8	37.1	**69.0**	8300
Sassali	0.04	0.03	0.24	**0.31**	5877
Salla	2.0	1.7	16.0	**19.7**	5777
Posio	2.0	1.5	15.6	19.2	6246
Tervola	2.1	1.5	15.5	19.1	6637

Across all research sites, the total RES potential is almost double the consumption (Tables 2–4). Typically, in the largest cities of Vaasa, Pietarsaari, and Kaskinen, the RES potential is only 19, 6, and 1% of the total consumption, respectively. Nevertheless, across the whole of Ostrobothnia, the potential is nearly 140%, and 2.5-fold the consumption when excluding the cities. In the sites of Southern Ostrobothnia, the potential is around twice the consumption, in the Kaustinen region 6.6-fold, and in Lapland three-fold.

Costs of energy in the research areas

The greatest potential in relation to consumption exists in the small villages of Siipyy, Tiukka, Dagsmark, and Jepua, in the municipalities of Närpiö, Pedersöre, Tervola, and Posio, and in the Kaustinen region. The balance is negative in some villages (Härkmeri, Lapväärti, Alahärmä) and municipalities (Luoto, Kruunupyy, Mustasaari, Kauhava, Kaustinen) due to the presence of industries and other larger enterprises. The RES potential without wind power is only some 18% of the total potential, which corresponds approximately to one-third of the total consumption over all of the research sites. Excluding the cities mentioned above, bioenergy (including biogas, energy from forestry, straw, and waste) covers around half of the consumption. This element of the potential is clearly more than the consumption in the smaller villages of Kallträsk, Metsälä, and Siipyy, Komossa, Jepu, and Sassali, and in the municipalities of Korsnäs, Lestijärvi, Salla, and Posio. The cities produce very little bioenergy resource, and their potential coverage in terms of bioenergy is also minimal in the more industrialized, yet rural, municipalities. Within the village sites, in contrast, bioenergy potential is 95% of the consumed electricity and heating energy combined. Correspondingly, the share is 85% across the municipality sites and only 12% in the cities. In Lapland, the bioenergy potential is 1.4–2.7-fold the electricity and heating energy consumption, with the exception of the municipality of Sodankylä with its mining industries. In Ostrobothnia, the share is 35% and, in the Kaustinen region, 106%.

The research sites, overall, spend nearly €1.4 Bn per year on energy purchases, of which ca. €1 Bn is used for transport, agriculture, and uses other than electricity and heating. Only €120 M goes toward heating, and €220 M for electricity. The sites in Ostrobothnia alone consume nearly €1 Bn per year in energy, 75% of which is used for purposes other than electricity and heating. The share of purchasing this part of energy varies between 74 and 90% overall, except in Pietarsaari (63%), Närpiö (61%), Sodankylä (53%), and Kaskinen (13%). The total cost of energy in the village sites is approximately €107 M per year. Electricity and heating cover only 7.4 and 7.7% of the total cost, respectively, while the other uses, excluding electricity and heating energy costs, covers 85%. In the cities, the share of electricity costs is 22%, and around two-thirds of the total sum of money is spent on energy, while €400 M is spent on transport. Within the municipality sites, the corresponding figures are 13 and 80% from a total of €1 Bn. The highest shares of electricity costs are in Kaskinen (80%), Sodankylä (41%), Närpiö (33%), and Pietarsaari (29%). The range of the share of heating costs is less than that of electricity and other energies, primarily being 10% or below, with exceptions of the city of Vaasa (ca, 15%), Kaustinen (12%), and Siipyy (12%). The average annual economic value of purchasing energy per capita is as high as €7400, with extremely high spending in Kaskinen (ca. €27000), Närpiö (ca. €10350), and Siipyy (ca. €10200).

Discussions

The potential of RESs exceeds the actual consumption of all forms of energy in small rural regions or EVs, excluding the larger industries. Wherever the villages have installed or planned wind power, the total RES potential is far larger than any consumption, including industries. Moreover, within larger regions, e.g., counties, the potential exceeds the consumption. Larger cities (Vaasa, Pietarsaari), industries (Kaskinen), and areas with energy-intensive businesses (Närpiö, greenhouse concentration) have negative balances even in rural regions: their RES potential would not cover their whole consumption. The rural areas surrounding these sites would, however, potentially cover all their energy demands, as well as those of the whole region. The potential of bioenergy will not suffice to cover more than one third of all the energy demands in county-level areas with the aforementioned energy-intensive sites. For them, the erection of wind turbines or other RE sources, such as solar power and ground-source energy (not calculated in this study), will be necessary to achieve regional self-sufficiency. Reaching this is still highly realistic, although some 90% of the wind potential is "only" at the planning stage: turbine erection is very actively underway in Finland, including within the research sites.

A national analysis of Finland's self-sufficiency energy potential[29] has shown that around 50% of all energy demands in Finland can be covered both by the RE already used and the unused and available bioenergy. In 2016, ca. 130 TWh/a of fossil-fuel energy was consumed; replacing this by renewables would require around 13,000 new 5 MW wind turbines. Since then, wind and solar power have been installed at an accelerating pace. These figures include all energies, including industries and the largest cities.

As for rural regions, the situation is dramatically different, as our research has shown. Even more than ten years ago, it was known that bioenergy alone could potentially cover all electricity and heating energy demands in rural Finland, and an extensive literature review showed the same globally[5]. Including the energy demands for transport, agriculture, and other purposes, however, changes the formula: to reach RES self-sufficiency even within smaller areas often requires other RESs besides bioenergy. The results can be applied on a global scale: even "…a megacity such as Delhi can benefit and drive a regional energy transition" and "develop local renewable energy resources to decouple from expensive overseas imports of fossil fuels," and thus "set an example for other megacities around the world…"[30]. In the island mode, "[t]he non-interconnected islands in Greece […] not scheduled to connect to the mainland grid will be converted into green energy islands"[31]. The results in this study support the presuppositions made in Section "Results", and the answer to the research question 1 is clearly positive. Therefore, the issue is not whether there would be sufficient RES to cover all energy demands, but how to implement sufficient RES production.

Since 2022, the Russian–Ukrainian war has led to an extremely unstable societal, political, and economic situation and has had a significant impact on the energy sector. The dependency on and restricted availability of Russian energy have led to a shortage of energy in Europe and considerably high energy prices. In this research study, it has been almost impossible to obtain reliable results concerning the economic situation, as the prices have not only been very high but have also been constantly changing, making it difficult to forecast some kind of "normal" situation. This complication also applies to the future: the exclusion of one major source of energy, the Russian fossil fuels, will affect the entire energy sector for a long time. Another impact will be the accelerated transition to renewable energies. This has been a high-level goal for most European countries and beyond, but many countries have found the required pace of change too great to achieve. The prospect of RES energy production, however, will be significant in any case, and this will provide rural regions with even more opportunities than previously anticipated. As practically all RESs are located and harvestable in rural areas[23], it is clear that these areas will focus not only on promoting the energy transition but will do so at an accelerated pace.

The results indicate the vast economic importance of energy, and directly highlight the potential significance of RES production for rural regions. It is also important to note that the prices used here even underestimate the real and future significance, as nearly all actual political and public discourses anticipate that prices will either remain high or will increase considerably. The other side of this coin is that the high energy prices may also improve the financial feasibility of RES-produced energy, owing to profitable implementation and mobilization. The logic of the economic development, studied in this article, can give the rural energy transition[23] a realistic boost. Energy transition can turn rural areas into arenas for the local promotion of eco-economies, in which RES form a central pillar[32]. In addition to the pure economic gain, the transition will add value to a region[6] with the introduction of completely new, entire value chains from RES harvesting to refining, as well as the delivery of energy, the management of regional systems, improved employment opportunities, societal benefits, and a new kind of rural vitality (cf[6,7,25,33–36]).

The impact of the energy transition on regional economies will be huge, even larger than previously observed[7]. In our sites, the economic value per capita most often exceeds 5000 euros per year. Within smaller villages, the total economic value already amounts to millions of euros; within municipalities of some 10,000 inhabitants, the figure can be as much as €50–80 M, and in counties of some 1,50,000 people, even €1 Bn. Although every investment must be independently feasible and profitable, the regional value, including the emerging new value chains close to the energy sources, might also motivate the public sector, mainly municipalities and their development companies, to participate in these investments, which could lower the threshold for investment for other regional stakeholders. In answer to research question 2, we state the following: the economic importance of rural regions, in particular, will be vast in the energy transition, and this may offer rural regions a central role in future energy management systems both nationally and globally.

This research gives clear, positive answers to our research questions: RES self-sufficiency is realistic both within smaller areas (EVs) and larger regions (counties, nationally). The implementation will be another issue and a longer societal process. The economic and regional economic potential is huge for rural areas. "Rural, sparsely populated, and economically underdeveloped regions […often with cheap land and small communities…] have thus become target areas for the installation of renewable energy facilities"[23]. This is completely in line with some previous observations and the eco-economic paradox: "rural areas have high ecological potential, yet low levels of economic activity (…) few welfare services"[37]. Rural regions could potentially fill this gap, as "…renewable energy constitute a key element of energy transitions and are inextricably tied to rural spaces"[23]. This clearly implies the importance of mobilizing rural resources. Summing up the potential for RES availability and both the business and regional economy may imply significant prospects for rural areas, even "… the emergence of a new role and potentiality for rural areas …"[37], the possible "productivist countryside"[38], meaning a new productive quality of rural areas, the actualizing potential of energy transition and the utilization of renewable energy with its business potential, employment prospects and rural vitality —the "regional value added"[6].

This might also offer farmers new positive motivation and interest to apply climate-beneficial measures, instead of being persuaded or forced (cf[39]) to reduce costs and generate income on the farm[40]. Farms could even play a key role in supporting rural community projects to develop RE production[40]. The remaining question is "…how and by what means new and revised production–consumption chains, networks and relationships can become established both within rural areas and between them and their urban neighbors"[37]. While RE is potentially important in rural development, "social acceptance defines decisions in renewable energy expansion in rural areas"[41]; this refers to the active and individual role of rural societies in choosing whether or not to take advantage of this opportunity. Consequently, despite the anticipated benefits, this concept is highly contested and is structured in three dimensions[23]: (1) while such resources are limitless, physical space is not; RES production may cause physical impacts (appearance, noise, odors, and landscape changes) and may also compete with other forms of land use (such as "food vs. fuel"). (2) One result can be the "financialization" of rural areas, which prioritizes investor profits over local distributive benefits (cf.[42]) and legitimizes the clearance of space, for instance, for wind farms[43]. The distribution of costs and benefits may be unfair. (3) Local decision making and participation[23], as well as community engagement by the public sector (e.g., municipalities) might be prioritized, where trust will be the key issue [13–15]).

There are still several questions remaining, such as who decides, who benefits, and who is affected by RES installations, etc., directly confronting the historical ways of exploiting natural resources, the resource peripheries' dilemma, ecological colonialism, and even robbery[21,44–48]). Moreover, history has shown a myriad of adverse impacts that cannot be categorized within the concept of sustainable energy or development (cf.[21]), even though the RE transition is poised to reduce the levels of the ecological footprint[22]. Therefore, the question is the same as in the general philosophy of utilizing natural resources: energy transition is part of a series of larger spheres, such as climate change abatement, the circular economy[47] and carbon neutrality (cf[23,37]). Nevertheless, the "post-carbon transitions will be mainly fought out in rural areas"[23].

The observations in our research, both currently and previously, indicate the very obvious development of rural energy transition, also supported by other researchers (e.g.,[23,32,37,38,42]). This also confirms our presuppositions, according to which the transition will be focused on solutions of a smaller scale, based on rural sources of energy and shorter-range logistics. This especially applies to forms of energy other than electricity, which have a more centralized system and an established transmission and delivery infrastructure, although electricity can also be produced in smaller-scale local and regional units. This development logically supports the previously introduced dichotomy vision[5], which sees the energy markets as on the brink of division into two overlapping strategies, viz., the prevailing centralized systems and the distributed systems in development. The new distributed energy management structure would serve the less populated rural areas and would provide energy for regional, even national, population centers and industries. In Finland, this would constitute roughly 90% of the whole country. The centralized system would then concentrate, in the future, on serving the largest population centers and the most energy-intensive industries. Both strategies would rely on RES, and they would ideally function in dialectical, unbroken collaboration and continuous co-development and synergy.

The data are also in line with the concept of rural areas supporting larger regions, including cities and even industries in their production of energy, by deploying all relevant renewable sources of energy. Therefore, the peripheral areas can provide the core sites (as named by Wallerstein[49]) or centers nationwide with energy services and natural resources sustainably. It remains to be seen what the division of labor and capital will be, and whether or not this might become a new target for ecological colonialism and robbery; perhaps there will be a new and positive transition enabling rural areas to benefit from their valuable, natural resources in a novel way. In summary, "…renewable energy sources belong to the core of rural capital, […] The development of a distributed energy model responds to societal needs and creates thousands of jobs in rural areas…" ([50] translated from Finnish). This is likely to provide rural areas with a completely new societal role: besides primary production and other traditional roles, the countryside can offer the whole nation renewable and sustainable energy. Support, however, is crucial because "…without leveraging and developing rural capital this will not materialise" ([50] translated from Finnish). Smart energy systems focus on "…achieving the goals of transitioning the energy system to become solely relying on renewable sources"[51] "by exploiting synergies through the integration of the various energy sectors—heating, cooling, electricity, transport and industrial—in a holistic approach where demand flexibility, storage optimization and production synergies can be used to better exploit the varying energy production from fluctuating renewable energy sources"[52].

Small rural regions, termed EVs, are potentially self-sufficient, due to the RES harvestable from within their own region, and most EVs would be able to produce energy or raw materials for energy for sale outside their region. In many areas, bioenergy alone would cover the energy demand; adding solar and wind power could potentially make all regions overproductive. The same applies to larger regions, comprising multiple small EVs. An increasing number of rural areas are capable of covering the energy demand of cities within the region, including industries located in that region. The economic potential is vast. The values used here were estimated before the Russian–Ukrainian war; therefore, it is not possible to provide a reasonable current value, other than that prices and the entire economic value of energy are expected to increase. As this is not a technical planning document, it includes no analysis of more precisely single, separate, or systemic regional solutions. The rural energy transition in all its forms will have a vast impact on the rural eco-economy and its vitality, even providing

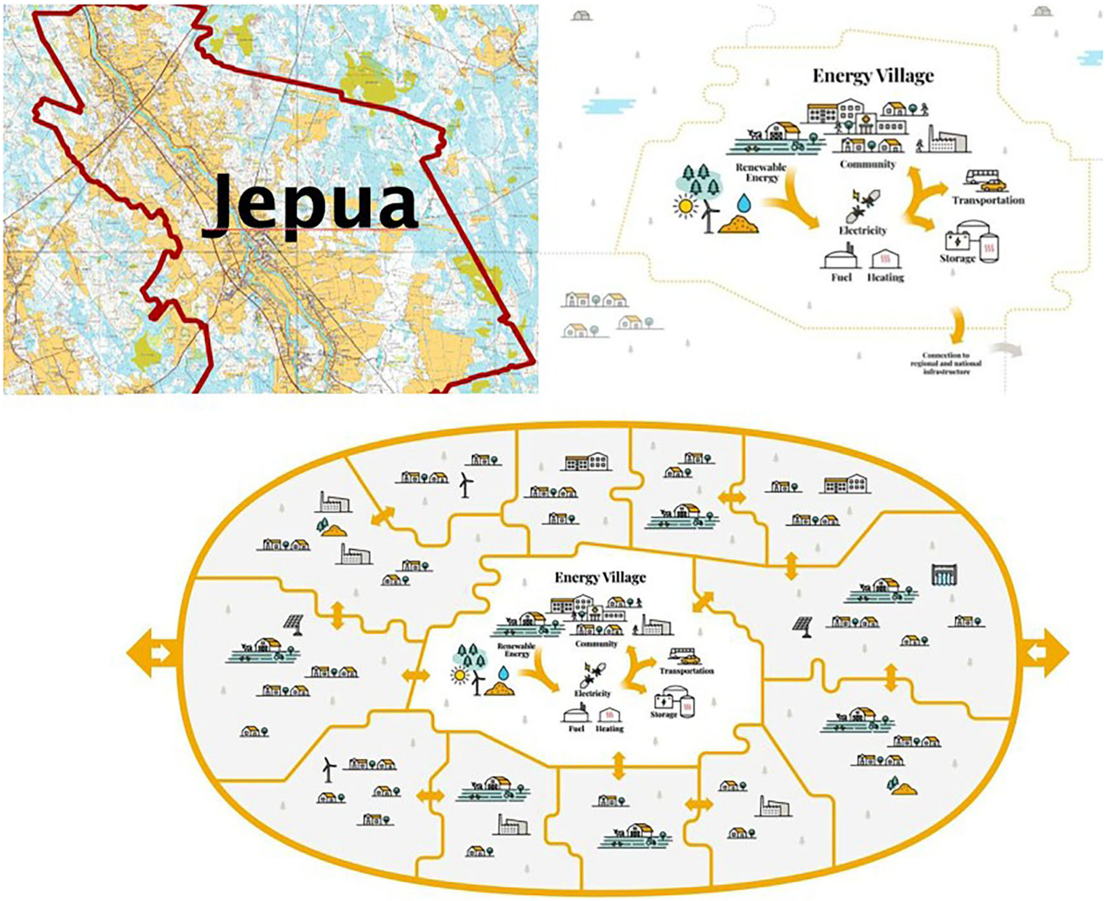

Fig. 1 | Jepua village (Western Finland, Uusikaarlepyy municipality; upper left), a conceptual presentation (upper right) as examples of EVs, and a schematic regional mosaic of EVs (lower).

rural regions with a new societal role: to serve the whole of society by producing sustainable RE.

The RES potential has been calculated as the total volume of energy, which only provides directional comprehension as regards the real potential. Some of the materials assumed might not be available in practice, but much of the potential has yet to be revealed: new free spaces, e.g., from turf refining, young forests, and even cultivation grounds may become available for both bioenergy and solar power production, to name but a few. Moreover, these calculations do not consider seasonal variations in the consumption, nor the seasonal intermittency of the RES production possibilities. The estimates of heating energy consumption are pretty vague, as the statistics are not up-to-date and are estimated by standard average use. Our intention here is only to show approximately where the path can lead and how best to follow it. The economic values used here were estimated before the disruptive change in energy prices across the entire energy market due to the Russian–Ukrainian war, as well as the turbulence of the Covid19 pandemic. As the war currently affects the prices and the markets overall, it will not be possible to predict any reasonable future values beyond linking figures to one particular point in time—in this case, the spring of 2022. What seems certain, however, is that prices and the whole economic value of energy will not be less than during the pre-war situation. The technical solutions for utilizing the RESs within each EV and region cannot be defined at this stage, and, for this reason, we are unable to present investment and feasibility calculations (capital, payback time, profitability) for the targets. Moreover, concerning the economy, the purpose is to show the potential magnitude of regional economies. In relation to single, separate investments or regional, systemic solutions, however, economic analyses remain to be conducted case by case after more precise technical planning.

Methods

From village to energy village

Defining ‘village’ and ‘energy village’. A village is a small settlement, a group of houses, usually in a rural setting, larger than a hamlet but smaller than a town. It can also be an incorporated minor municipality, a territorial area having the status of a village, especially as a unit of local government, smaller than a town and including the inhabitants of such a community collectively, e.g.,[53–55]. In scholarly contexts, the conceptualization of villages and of villagers’ roles has mainly been based on “… the village as an economic entity and a major base for the livelihood of its inhabitants”[56]. In the 1970s, villages were predominantly agricultural communities. In the 1990s, the roles were about to change: “With the ever-smaller role of agriculture for the villagers, the residential function of the village gained more and more attention”[56].

In the 2010s, “…the conditions are so manifold and various that no measure of agricultural policy is able to meet the needs of the entirety of small farmers…”[56]. Changes unfolded in the conditions of local populations and local heterogeneity: “…the villages changed from being the location of small family farms towards socially and economically differentiated places”, and this change also encompassed “…growing mobility, urbanization and internationalization”[56]. Even though villages are “… strongly interwoven with their surroundings”[56], their relationships with the natural resources around them have barely been explored. In this article, we pay less attention to the social dimensions of the villages, although these will certainly have importance as regards the implementation of the SET procedures, and focus mainly on the RESs in their surroundings. The major hypothesis is that a larger region consists of smaller units, referred to here as EVs (Fig. 1). These EVs are defined as follows:

Fig. 2 | Research areas.

- An EV is a small town or region, a mixture of houses, small commercial and industrial properties, or local authority-owned buildings and farms, akin to the typical village concept described above.
- An EV also comprises the surrounding impact area, for example, forests, open countryside, or cultivation grounds with their associated RES potential.

The EV idea corresponds to that of energy islands, as EVs can be defined in such a way that they are completely or nearly isolated from the wider energy grid and, from an external perspective, can be treated almost as a single energy-consuming and producing entity.

Theoretically, larger regions, such as municipalities or counties, can be divided into EVs that border one another and, in union, cover the whole region.

Typically, EVs are situated in rural locations, where most of the RESs can be harvested and utilized, but, correspondingly, independent units can also be identified, such as suburbs, blocks of houses, or even single houses, which are essentially independent energy management units.

The energy village design concept for small areas

The EV is also a replicable concept for creating small regions which are RES self-sufficient, with a particular focus on rural areas. The aim is to bring small, primarily rural regions to a state of 100% + RE self-sufficiency, using local RES. A "normal" EV is a small village, town, or region, with a population of 50–10,000 inhabitants, with a mixture of houses, small commercial and industrial properties, local authority-owned buildings, and farms, but also the surrounding impact area with associated RES potential. The concept is based on the idea of SE, which goes beyond the use of RES to encompass also an overall reduction of energy use. It integrates relevant technologies into systemic solutions and requires sustainability management to avoid adverse impacts. This provides the common methodological base for the EV concept, encompassing digitalized applications and tools. This toolkit can be widely disseminated and made available to potential replicators to boost SE implementation. The focus is on rural-area EVs (communities, districts, or regions) with a significant and increasing share of distributed, low- and zero-carbon renewable electricity, heating, cooling, and transport fuel generation from local resources, electric or thermal storage, and flexible demand, and controllable loads. Electricity can be distributed over both medium (MV) and low-voltage (LV) networks, or LV only, depending on the size of the village.

The EV concept is grounded on the following presuppositions:

- Each EV primarily covers its own energy demand with RESs from within its own area. The energy balance, however, depends on the demography, industrial structure, and other characteristics of the EV. Each EV's energy balance collates and compares the consumption of energy (all vectors) with the RES potential from the whole EV surface. Initial estimates of the balance should be refined by research.
- In most EVs, especially rural ones, the balance is usually positive, meaning that the EV can also produce energy (or raw materials for producing energy) for sale.
- RESs are usually materials left over from other activities, not used for any other purpose. This results in the efficient utilization of unused but available, cheap, and local materials [57].
- One of the most important drivers for the local and regional use of RESs is the potential to improve the regional economy, by replacing purchases of (usually fossil) energy from outside with local and regional activities (cf.[7]).

In summary, the assemblage of EVs within a larger region will, in many cases, be supposed capable of serving societies outside the region itself. This potential is, however, a question to be confirmed by research, and, in some cases, the balance might be negative.

EVs, municipalities and regions

The research sites and some of their main characteristics have been listed in Table 1, and mapped in Fig. 2. The sites include 16 villages and 27 municipalities in total, located in the Ostrobothnia, Central Ostrobothnia (Kaustinen Region), Southern Ostrobothnia, and Lapland counties. In Ostrobothnia, this includes the largest cities of Vaasa and Pietarsaari, while all the other sites are rural municipalities and villages, including the smaller rural cities of Kristiinankaupunki and Uusikaarlepyy, both having large rural areas and villages. The economic structure is dominated by a high proportion of primary production across all rural sites, while Vaasa and Pietarsaari are typically industrialized and are service-oriented cities. Vaasa has the largest energy technology industry concentration within Northern Europe, with large, globally-active enterprises, such as ABB, Wärtsilä, Danfoss, and The Switch, etc., currently employing more than 11,000 people.

The rural sites, especially within the Ostrobothnian counties, also have remarkably low levels of unemployment, which is typical in agriculturally dominated areas, accompanied by a tradition of entrepreneurship (e.g.,[58]).

This, however, does not apply to the northern sites in Lapland, where unemployment is a difficult problem. The high proportion of services results from the centrality of tourism in Lapland. The total research area, ca. 35,000 km^2, is ca. 11.5% of Finland's total land mass. Correspondingly, the population within the research sites, ca. 2,41,000 inhabitants, represents some 4.4% of the national total. The mainly rural sites are, on average, more sparsely populated than other areas in Finland. The population in the research area villages ranges from 49 to 53 in Kallträsk and Sassali, respectively, to 1240 in Perho municipal center, while Alahärmä (2330 inhabitants) and Vähäkyrö (5360 inhabitants) are formerly independent municipalities and now parts of the cities of Kauhava and Vaasa, respectively. "During the first two decades of the twenty-first century, the introduction of policies that promote renewable energy in Western European countries facilitated a shift towards the production of cleaner energy and its decentralization"[59]. This study is a continuation of such progress.

Energy balances in the research areas

The energy, by village, municipality, and region were defined by calculations and the comparison of energy demand and RES potential, both of which are briefly described below.

Energy demand

Energy demand figures were mainly collated or calculated according to published statistics and complementary interviews. Energy demand consists of the use of electricity, heating energy, and transport fuels, including machines within agriculture. The methods used are listed in Table 6.

The data for the total actual use of electricity in regions and municipalities were taken from official statistics, which originate from metered data and reports by energy utilities[60]. Village-specific demand was estimated from the average demand within the larger area, scaled to each village's population (population data[61]: web pages of the villages). The heating energy usage includes all buildings (public and private houses, industrial and business premises). The number of all houses and premises and their surrounding areas has been obtained from official statistics[61,62]). These figures were refined into heating demand as shown in the Appendix, and include the electricity used for heating. Transport fuel consumption was calculated as a simple multiplication of vehicle and machine numbers, average distances driven or hours used, and average consumption, calculated separately for different regional units and different vehicle categories, as follows:

- Regional units: villages, municipalities, and the two regions.
- Number of vehicles by category: light traffic including personal vehicles, heavy traffic including buses, trucks, tractors and farm machinery; numbers, average consumption, estimated distances for regions and municipalities[61]: numbers for villages in relation to the population.

The average figures for fuel consumption and distance or use per year for the various vehicle categories are provided in the Appendix. The number of vehicles in each region, by category, was obtained from the municipalities for villages and municipalities, and from the national statistics for the regions. The average consumption, the distances, and hours of use were taken from the national statistics[61].

Table 6 | Summary of the methods used for obtaining energy demand figures

Demand	Method	Source
Electricity	Municipalities: Official statistics Villages: In relation to the population	Energy Industry 2021
Heating	Calculation based on building areas and average heat demand according to statistics	Statistics Finland 2022 Interviews
Transport fuel Light traffic: passenger cars and vans Heavy traffic: trucks and buses Farming machines	Municipalities: Average distance by vehicle and average consumption multiplied by the number of vehicles; Statistics by area Villages: In relation to the population Separately: Light and heavy traffic, and farming machines	Municipalities Statistics Finland 2022 Interviews

RE potential metrics

There are several definitions of RE supplies in the literature, adequately summarized by[63] and[64]). The supply, from several types of sources, is "…obtained from the continuing or repetitive currents of energy occurring in the natural environment and includes non-carbon technologies such as solar energy, hydropower, wind, tide and waves and geothermal heat, as well as carbon-neutral technologies such as biomass"[64]. These sources have been described in more detail by e.g.,[63] and[65]. In this study, bioenergy and wind power have been considered, and, in some cases, there are also small-scale contributions from solar and hydro power. These energy sources do occur in the study areas: there are industries refining some of the sources, there is infrastructure for their utilization (e.g., in forestry), and their energy content can be measured reliably. Other forms of RES have not been considered because they are either unavailable in Finland or the technology is still underdeveloped for wider utilization. The figures for the energy content of each RES were calculated or collated separately from within the defined borders for each region, municipality, and EV. The methods for obtaining the data are described briefly below and are summarized in Table 7.

The bioenergy potential data have been collected from the Biomass Atlas, which was created and is maintained by the Natural Resources Institute Finland[66], and which is based on the latest available scientific knowledge. The potential does not include areas, materials, or products for food or other industrial production. Therefore, the potential collates materials and side product flows that are not actively utilized for any other purposes currently. For instance, wood-based materials from forestry are a combination of logging residues and culls from thinning young forests. The

Table 7 | Summary of the methods for obtaining bioenergy supply figures

Fraction	Method	Source
Manure	Number of domestic animals; classified by species and sub-groups: cattle, pigs, fur animals	Municipal officers Ministry of Agriculture and Forestry
Sludge	Official statistics	Municipalities; Environment administration
Biomass from cultivation grounds	Reed canary grass crop (tons/ha) potential from fallowed areas: Silage (10%), fertilization grass, fallowed fields, fields for environmental management	Municipalities Ministry of Agriculture and Forestry
Wood	Logging residues only; Actual data from loggings	Regional Forestry Centers
Straw and other cultivation residues	Cultivated areas; Specific harvest and energy content for species	Municipalities Ministry of Agriculture and Forestry
Municipal biowaste	Official statistics	Environment administration

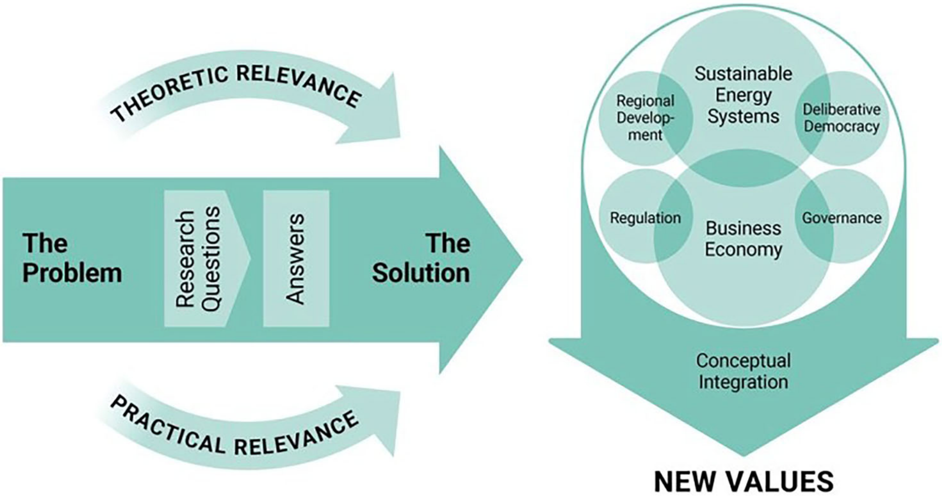

Fig. 3 | The constructive research process from problem to solution, with reference to theoretic and practical relevance (left; redrawn[21,83]) and the principle of conceptual integration (right; redrawn[21]).

energy potential of straw combustion has been calculated based on 50% utilization of the annual yield for cultivated grain[66]. Waste incineration figures include the separately collected combustible solid municipal waste, usually ca. 450 kg/annum per capita in Finland, with an energy content of 2.5 kWh/kg; the energy yield has been presupposed to be 85%[66]. All quantities were multiplied into energy content units via generally available and commonly used specific values (e.g.,[64,67–70]). The biogas potential was calculated based on the share of total (TS) and volatile solids (VS) and material-specific gas production ([67,69]). All quantities were then multiplied into energy content units using generally available and commonly used specific values ([68–70]).

Wind power has been considered for the already existing turbines and turbines under construction; the projected wind parks currently under permitting procedures have also been included in the RES potential. The data were obtained from refs. 71,72 considering the efficiency of 2400 operative hours yearly (some 27%). The figures for hydro power, present in a few of the research areas (multiplication of the number of turbines, operational hours per year, and operational efficiency), include data from existing power stations that have already been in use for decades. The erection of new hydro power stations has been negligible, as most of the remaining waterfalls that would be suitable are protected by law. The research target areas were villages or sub-regions of municipalities. As most of the statistics have been collected by the municipalities, the material was mainly obtained via personal contact in these areas. All of the villages were visited, where interviews took place face-to-face. The people contacted fell into the following categories: municipal officers (technical directors, environmental, rural, and business managers), personnel from the regional energy utilities or from development organizations and enterprises.

This compilation of bioenergy metrics, based on official statistics and relevant specific figures and considering geographical features, corresponds to the harmonization methods proposed for the EU[64]. In the literature, this method of using official statistics as a starting point, multiplied by specific values and taking geographical characteristics into account, is typical: for example, for the potential of global field biomass[70], global bioenergy[72,73,74]), global sustainable biomass energy[75,76]), global bioenergy from forestry[77], and overall RES on a global scale[78]. Wind and solar power are, in principle, inexhaustible, especially over small areas, and they have been included not as mere potential, but as actual existing energy sources or sources under development, or as examples of how many production units would cover a certain energy demand.

Economic value of energy

The economic value of energy was calculated for all regional categories according to the Spring 2022 energy prices: electricity: 0.052 €/kWh (excluding VAT and delivery); gasoline, diesel, and oil: 1.9 €/l. All prices are without VAT, and the electricity price does not include delivery costs. The price for heating was calculated by multiplying the unit price of the fuel by the total area per building category by municipality. The total building areas by municipality were divided into building categories, using the national average proportions[61], since no specific data were available concerning these categories in the municipalities. Each heating method uses a specific fuel, each of which has a different price. It is presupposed that all the money currently spent on energy will also be used for energy in the future. The share of energy, presumed to be produced by various technical solutions, would differ between regions, depending on local characteristics, so it was not possible to conduct a deep and thorough economic analysis. The pre-existing data regarding the division of money flow along the main value chains (biogas, CHP, wind power) allowed a rough and indicative estimate of the money flow for the whole RES-based production of energy. The overall idea is to show the economic dimension and potential, and, in practice, the intention has been to motivate and activate the various stakeholders in the villages.

Research gap, novelty and approach

We address the following knowledge gaps and scientific novelties:

The approach gap: as SET is a societal process, it will be necessary to create understanding, reflecting all the relevant branches of knowledge. We add value to this by introducing the philosophical level of conceptual integration.

The regional gap: there is a knowledge gap regarding the location of harvestable RES, which will be crucial in relation to the implementation of sustainable energy. We address this gap by studying (energy) villages, regions consisting of villages, and the ability of these entities to serve not only the region and the villages themselves, but also the continuum from villages to larger societies, even cities, through the utilization of RES. We highlight the importance of rural regions and the traditional periphery–center logic.

The regional economy gap: knowledge and understanding of the regional economic potential and the significance of utilizing each region's own renewable yet unused resources, are still very vague. We address this gap by analyzing the economic value of energy and how regions would benefit if fossil energy were to be replaced by RES, within each region firstly, but with potential for sale to other regions.

The systems gap: The mainstream way of understanding the SET has been based on single, separate technical solutions, largely neglecting how to create understanding towards systemic solutions. We prepare the ground by introducing the energy village concept, where the wholeness consists of several single and separate solutions, integrating the societal processing and stakeholders within the targets, and considering the societal restructuring under the emergence of new regulations and continuously developing innovations, for instance. A holistic diagnosis and holistic approach to solving the problem are lacking, as "…the uptake of energy crops and renewable energy derived from agricultural biomass is determined by a combination of interlinked, multidimensional political, institutional, cultural, and economic processes, not just technological ones" ([79] cf.[59]), and "The integration of knowledge and practice from different scientific disciplines is essential to achieving the overarching objectives of renewable energy projects that are important in the long term for communities and collectives"[79].

These quotes encapsulate the research gap addressed and the importance of the approach adopted in this research: we aim to understand highly practical problems by scientific means, which epitomizes the constructive approach. We also integrate knowledge from several disciplines, referring directly to the philosophy named conceptual integration. Therefore, this research falls within the constructive approach. This is a type of applied study which, by its philosophical nature, focuses on technical norms. The constructive approach is intentional, characterized by the aim of producing new knowledge, applications, or results (Fig. 3[80,81]). It is important to highlight the SET reflecting all the relevant branches of knowledge. This implies the importance of the philosophical approach of conceptual integration, which "… requires that the postulates of different branches of science are compatible in a meaningful way to each other"[82]. Instead of violating, reducing or simplifying the independent achievements of the different branches of knowledge, conceptual integration explains and merges the background presuppositions into larger intellectual entities. It can integrate the originally different and separate explanations into chains, creating an important philosophical level of managing and understanding the ever-growing amount of knowledge and giving it meaning (e.g.,[82]). An example of applying conceptual integration has been illustrated in Fig. 3.

Data availability

No datasets were generated or analysed during the current study.

Code availability

Data kept for future use and not willing to share and there is no coding used.

Received: 28 October 2025; Accepted: 25 January 2026;

References

1. Peura, P. From malthus to sustainable energy—theoretical orientations to reforming the energy sector. *Renew. Sustain. Energy Rev.* **19**, 309–327 (2013a).
2. Johnston, P., Everard, M., Santillo, D. & Robért, K.-H. Reclaiming the definition of sustainability. *Environ. Sci. Pollut. Res. Int.* **14**, 60–66 (2007).
3. Chichilnisky, G. What is sustainability?. *Int. J. Sustain. Econ.* **3**, 125–140 (2011).
4. Peura, P. & Sjöholm, P. Sustainable or distributed energy – or both? clarifying the basic concepts of reforming the energy sector. *AIMS Energy* **3**, 241–254 (2014).
5. Peura, P. & Hyttinen, T. The potential and economics of bioenergy in Finland. *J. Clean. Prod.* **19**, 927–945 (2011).
6. Hoffmann, D. Creation of regional added value by regional bioenergy resources. *Renew. Sustain. Energy Rev.* **13**, 2419–2429 (2009).
7. Peura, P., Haapanen, A., Reini, K. & Törmä, H. Regional impacts of sustainable energy in Western Finland. *J. Clean. Prod.* **187**, 85–97 (2018).
8. Wüstenhagen, R., Wolsink, M. & Bürer, M. J. Social acceptance of renewable energy innovation: an introduction to the concept. *Energy Policy* **35**, 2683–2691 (2007).
9. Connolly, D., Lund, H. & Mathiesen, B. V. Smart Energy Europe: the technical and economic impact of one potential 100% renewable energy scenario for the European Union. *Renew. Sustain. Energy Rev.* **60**, 1634–1653 (2016).
10. Unruh, G. C. Escaping carbon lock-in. *Energy Policy* **30**, 317–325 (2002).
11. Jacobsson, S. & Johnsson, A. The diffusion of renewable energy technology: an analytical framework and key issues for research. *Energy Policy* **28**, 625–640 (2000).
12. Bergek, A. Levelling the playing field? The influence of national wind power planning instruments on conflicts of interests in a Swedish county. *Energy Policy* **38**, 2357–2369 (2010).
13. Wolsink, M. Wind power and the NIMBY-myth: institutional capacity and the limited significance of public support. *Renew. Energy* **21**, 49–64 (2000).
14. Wolsink, M. Planning of renewables schemes. Deliberative and fair decision-making on landscape issues instead of reproachful accusations of non-cooperation. *Energy Policy* **35**, 2692–2704 (2007).
15. Wolsink, M. The research agenda on social acceptance of distributed generation in smart grids: Renewable as common pool resources. *Renew. Sustain. Energy Rev.* **16**, 822–835 (2012).
16. Lund, H. *Renewable Energy Systems. The Choice and Modeling of 100% Renewable Solutions*? (Academic Press, 2010).
17. Narouzi, F., Hoppe, T., Elizondo, L. R. & Bauer, P. A review of socio-technical barriers to Smart Microgrid development. *Renew. Sustain. Energy Rev.* **167**, 112674 (2022).
18. McCormick, K. & Kåberger, T. Key barriers for bioenergy in Europe: economic conditions, know-how and institutional capacity, and supply chain co-ordination. *Biomass-. Bioenergy* **31**, 443–452 (2007).
19. Blarke, M. B. *From dusk till dawn. An essay about how the climate crisis has come to define sustainable energy in the context of the Danish experiment* (Aalborg University, 2008).
20. Moriarty, P. & Honnery, D. What energy levels can the Earth sustain?. *Energy Policy* **37**, 2469–2474 (2009).
21. Peura, P. *From Unlimited Growth to Sustainable Energy. The origin of operational patterns by means of social selection*. Acta Wasaensia 279. Doctoral dissertation (2013b).
22. Afshan, S., Ozturk, I. & Yaqoob, T. Facilitating renewable energy transition. ecological innovations and stringent environmental policies to improve ecological sustainability: evidence from MM-QR method. *Renew. Energy* **196**, 152–160 (2022).
23. Naumann, M. & Rudolph, D. Conceptualizing rural energy transitions: energizing rural studies. ruralizing energy research. *J. Rural Stud.* **73**, 97–104 (2020).
24. Overland, I., Javlon, J. & Vakulchuk, R. Are renewable energy sources more evenly distributed than fossil fuels?. *Renew. Energy* **200**, 379–386 (2022).
25. Sastresa, E. L., Usón, A. A., Bribián, I. Z. & Scarpellini, S. Local impact of renewables on employment: assessment methodology and case study. *Renew. Sustain. Energy Rev.* **14**, 679–690 (2010).
26. Ortega, M., del Río, P., Ruiz, P. & Thiel, C. Employment effects of renewable electricity deployment. A novel methodology. *Energy* **91**, 940–951 (2015).
27. Többen, J. Regional net impacts and social distribution effects of promoting renewable energies in germany. *Ecol. Econ.* **135**, 195–208 (2017).
28. Markandya, A., Arto, I., Gonzáles-Equino, M. & Román, M. V. Towards a green energy economy? Tracking the employment effects of low-carbon technologies in the European Union. *Appl. Energy* **179**, 1342–1350 (2017).
29. Peura, P. et al. Hajautetun uusiutuvan energian mahdollisuudet ja rajoitteet (HEMU; in Finnish. Opportunities and limitations of distributed energy). *Publications of the Government's analysis, assessment and research activities* 35/2017. 109 pp. Available at: http://urn.fi/URN:ISBN:978-952-287-382-8 (2017).
30. Ram, M., Gulagi, A., Aghahosseini, A., Bogdanov, D. & Breyer, C. Energy transition in megacities towards 100% renewable energy: a case for Delhi. *Renew. Energy* **195**, 578–589 (2022).

31. Dimou, A. & Vakalis, S. Technoeconomic analysis of green energy transitions in isolated grids: the case of Ai Stratis – Green Island. *Renew. Energy* **195**, 66–75 (2022).
32. Magnani, N., Maretti, M., Salvatore, R. & Scotti, I. Ecopreneurs, rural development and alternative socio-technical arrangements for community renewable energy. *J. Rural Stud.* **52**, 33–41 (2017).
33. del Río, P. & Burguillo, M. An empirical analysis of the impact of renewable energy deployment on local sustainability. *Renew. Sustain. Energy Rev.* **13**, 1314–1325 (2009).
34. Openshaw, K. Biomass energy: Employment generation and its contribution to poverty alleviation. *Biomass-. Bioenergy* **34**, 365–378 (2010).
35. Dalton, G. J. & Lewis, T. Metrics for measuring job creation by renewable energy technologies. using Ireland as a case study. *Renew. Sustain. Energy Rev.* **15**, 2123–2133 (2011).
36. Masini, A. & Menichetti, E. The impact of behavioural factors in the renewable energy investment decision making process: Conceptual framework and empirical findings. *Energy Policy* **40**, 28–38 (2012).
37. Kitchen, L. & Marsden, T. Creating sustainable rural development through stimulating the eco-economy: beyond the eco-economic paradox?. *Sociologia Ruralis* **49**, 273–293 (2009).
38. Cowel, R. Wind power, landscape and strategic, spatial planning – the construction of 'acceptable locations' in Wales. *Land Use Policy* **27**, 222–232 (2010).
39. Farstad, M., Mahlum Melåsa, A. & Klerkx, L. Climate considerations aside: what really matters for farmers in their implementation of climate mitigation measures. *J. Rural Stud.* **96**, 259–269 (2022).
40. Morris & Bowen. "Renewable energy diversification: considerations for farm business resilience." *J. Rural Stud.* **80**, 380–390 (2020).
41. Apostolopoulos, N., Chalvatzis, K. J., Liargovas, P. G., Newbery, R. & Rokou, E. The role of the expert knowledge broker in rural development: renewable energy funding decisions in Greece. *J. Rural Stud.* **78**, 96–106 (2020).
42. Marsden, T. Exploring the rural eco-economy: beyond neoliberalism. *Sociol. Rural.* **56**, 597–615 (2016).
43. Rudolph, D. & Kirkegaard, J. Making space for wind farms: practices of territorial stigmatisation in rural Denmark. *Antibode* **51**, 642–663 (2019).
44. Worster, D. *The ends of the earth. Perspectives on modern environmental history* (Cambridge University Press, 1988).
45. Ponting, C. *A Green History of the World* (Penguin Books, 1992).
46. Crosby, A. W. *Ecological imperialism. The biological expansion of Europe. 900–1900* (Cambridge University Press, 1996).
47. Livi-Bacci M. *A Concise History of World Population* (Blackwell, 1999).
48. McNeill, J. R. *Something new under the sun. An Environmental History of the Twentieth-Century World* (Norton, 2001).
49. Chase-Dunn, C, Smith, J, Manning, P. & Grubacic, A. "Remembering Immanuel Wallerstein." *J. World-Syst. Res*. **26**, https://doi.org/10.5195/jwsr.2020.995 (2020).
50. Katajamäki H. *Viileä järki. innostuksen aate. Konkreettiset utopiat paikkaperustaisen politiikan edistäjinä*. Ruralia Institute (University of Helsinki, 2021).
51. Lund, H., Østergaard, P. A., Connolly, D. & Mathiesen, B. V. Smart energy and smart energy systems. *Energy* **2017**, 556–565 (2017).
52. Lund, H., Østergaard, P. A., Duic, N. & Mathiesen, B. V. Special issue on smart energy systems from the 7th SESAAU2021 conference. *Energy* **263**, 125975 (2023).
53. *Collins online dictionary* https://www.collinsdictionary.com/dictionary/english/village; visited June 22nd (2022).
54. *Merriam-Webster dictionary* https://www.merriam-webster.com/dictionary/village; visited June 22nd (2022).
55. *National Geographic* https://education.nationalgeographic.org/resource/village; visited June 22nd (2022).
56. Tuitjer, G. & Steinführer, A. The scientific construction of the village. Framing and practicing rural research in a trend study in Germany. 1952–2015. *J. Rural Stud.* **82**, 489–499 (2021).
57. Peura, P., Voutilainen, O. & Kantola, J. From garbage to product and service systems: a longitudinal Finnish case study of waste management evolution. *Waste Manag.* **140**, 143–153 (2022).
58. Katamäki, H. Alueellisen työnjaon muotoutuminen Suomessa. (in Finnish; The formation of the spatial division of labour in Finland) pp. 144 (*Publicationes Instituti Geographici Universitatis Turkuensis,* 1988).
59. Soares da Silva, D. & Horlings, L. G. The role of local energy initiatives in co-producing sustainable places. *Sustain. Sci.* **15**, 363–377 (2020).
60. Energy industry www.energia.fi/tilastot/sahkotilastot (2021).
61. Statistics Finland https://stat.fi/tilastotieto (2022).
62. Kartta https://kartta.com/postinumerohaku/ (2022).
63. Verbruggen, A. et al. Renewable energy costs. potentials. barriers: conceptual issues. *Energy Policy* **38**, 850–861 (2010).
64. Doukas, H. et al. A methodology for validating the renewable energy data in EU. *Renew. Energy* **32**, 1981–1998 (2007).
65. Ragwitz, M. et al. *Analyses of the EU renewable energy sources' evolution up to 2020 (FORRES 2020),* (Fraunhofer IRB, 2005).
66. Luke. *Biomass Atlas*. Natural Resources Institute Finland. Available at: https://biomassa-atlas.luke.fi/?lang=en (2021).
67. Turunen T. *Maatalousjätteiden termofiilinen biometanointi ja biometanoidun jätteen jatkojalostus*. (In Finnish; Thermophilic biomethanisation of agricultural waste and further refining of the process waste from biomethanisation). Pro gradu thesis. Bio and environmental sciences. (University of Jyväskylä, 1999).
68. Alakangas, E. *Suomessa käytettävien polttoaineiden ominaisuuksia*. (In Finnish; Characteristics of fuels used in Finland) (2000).
69. Uusi-Penttilä, P. *Biokaasun liikennekäyttö Jyväskylän seudulla. (In Finnish; Traffic use of biogas in Jyväskylä Region) (Jyväskylä: Jyväskylä Science Park.*, 2004).
70. Finbio. *Energy units and transforming coefficients*. http://www.finbioenergy.fi/ (2005).
71. Tuulivoimayhdistys www.tuulivoimayhdiustys.fi (2021).
72. Hakala, K., Kontturi, M. & Pahkala, K. Field biomass as global energy source. *Agric. Food Sci.* **18**, 347–365 (2009).
73. Fischer, G. & Schrattenholzer, L. Global biomass potentials through 2050. *Biomass-. Bioenergy* **20**, 151–159 (2001).
74. Smeets, E. M. W., Faaij, A. P. C., Lewandowski, I. M. & Turkenburg, W. C. A bottom-up assessment and review of global bio-energy potentials to 2050. *Prog. Energy Combust. Sci.* **33**, 56 (2007).
75. Ladanai, S. & Vinterbäck, J. *Global Potential of Sustainable Biomass for Energy*. 29 (*University of Agricultural Sciences*, 2010)
76. Ceciliano, R. WBA's report shows: the global potential of sustainable bioenergy is enough to meet the world's total energy needs. *Bioenergy* **3**, 4–5 (2010).
77. Smeets, E. M. W. & Faaij, A. P. "Bioenergy potentials from forestry in 2050. *Clim. Change* **81**, 353–390 (2007).
78. Resch, G. et al. Potentials and prospects for renewable energies at global scale. *Energy Policy* **36**, 4048–4056 (2008).
79. Myna, A. & Dobrowolski, J. Renewable energy derived from agricultural biomass in peripheral rural areas: 'Vicious circle', Gordian knots', and turning points. *J. Rural Stud.* **82**, 222–232 (2021).
80. Kasanen, E., Lukka, K. & Siitonen, A. Konstruktiivinen tutkimusote liiketaloustieteessä." [in Finnish: "The Constructive Approach in Management Accounting Research. *Finnish J. Bus. Econ.* **3**, 301–325 (1991).
81. Kasanen, E., Lukka, K. & Siitonen, A. The constructive approach in management accounting research. *J. Manag. Account. Res.* **5**, 243–264 (1993).
82. Ylikoski, P. & Kokkonen, T. *Evoluutio ja ihmisluonto*. [in Finnish; *Evolution and human nature*] (Helsinki, 2009).
83. Rautiainen, A., Sippola, K. & Mättö, T. Perspectives on relevance: the relevance test in the constructive research approach. *Manag. Account. Res.* **34**, 19–29 (2017).

Acknowledgements

Sincere gratitude goes to Professor Pekka Peura and Professor Erkki Hiltunen for letting Nebiyu Girgibo work on this paper, and the related work placement. In addition, we would like to thank all our workmates here at the University of Vaasa, School of Technology and Innovations, Department of Energy Technology and Vaasa Energy and Business Innovation Center (VEBIC). We also love to thank all the staff of University of Vaasa who participated in the projects of Energy Village concept. As all the Finland citizens especially, those in the Energy Village areas highly acknowledged for their willingness, thankfulness and contributions. We would also like to thank very much for publication financial support from project called Long-Term Joint European Union - African Union Research and Innovation Partnership on Renewable Energy (LEAP-RE).

Author contributions

Pekka Peura: Writing—original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. Ari Haapanen: Writing—review and editing, Writing—original draft, Funding acquisition. Nebiyu Girgibo: Writing—review and editing, Writing—original draft.

Competing interests

There are duplicated publication materials used on this paper. Both the publications are ours and it has been used with reference. These adaptions were done due to the fact that the figures taken are similar sites and they are important to this publication.

Consent for publication

All the authors agreed and gave their consent for publication.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s44406-026-00021-z.

Correspondence and requests for materials should be addressed to Nebiyu Girgibo.