Slashing the surplus

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Slashing the surplus – how prosumers with smart metering respond to regulatory restrictions on self-consumption in Croatia

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Abstract With the diffusion of prosumerism, where households act both as producers and consumers of energy, policy makers must strike a balance between encouraging microgeneration and regulating this new prosumer segment on the energy market. However, effective policy implementation depends on prosumers' behavioural reactions. This paper provides evidence on the interplay between digital real-time information and regulation of self-consumption for rooftop photovoltaics (PV) in Croatia. Croatian households that produce more annual electricity than they consume are automatically re-classified as renewable traders, which means additional administrative duties and less favorable tax treatment. This creates perverse incentives to reduce PV generation or increase energy consumption by year-end. We document the behavioural reactions to this policy design, indicating that energy production and consumption are highly elastic regarding regulatory incentives, but only if these incentives are made transparent and accessible with timely information. We collected two survey waves ($n=54$ and $n=80$) and smart meter data ($n=39$), which illustrate the behavioural reaction before and after year-end. According to the survey wave before year-end, almost half of the participants considered curtailing their PV output. According to the smart meter data, a sizable share did indeed take action by shutting down PV production or by powering additional devices to reduce the surplus near year-end. In a second survey wave in the new year, prosumers provide ex-post insights on the specific measures taken to reduce surplus. We discuss research insights regarding the transparency and control offered by metering feedback, and how this can influence household behaviour within regulatory frameworks.

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Introduction

Motivation

Prosumers, i.e. households that act both as producers and consumers of energy, are increasingly recognized as players in the energy transition (European Environment Agency, 2022). Through digital tools like smart metering and Home Energy Management Systems (HEMS), they may optimize self-consumption by actively managing production and consumption (see Cappa et al., 2020). However, whether prosumers actually adopt such behaviour (or not) depends heavily on the overarching policy frameworks that regulate their access to the energy market (Gautier et al., 2019; Klein et al., 2019).

Policy makers must strike a balance between encouraging microgeneration in the residential sector through awareness measures and policy support, while also respecting external constraints arising from broader policy objectives in both the energy system and the tax system (see Wood et al. (2016) for a comparison of perspectives, Gržanić et al. (2016) for specifics of prosumer policy). Important constraints in this context are ensuring that prosumers contribute adequately to network cost recovery (energy system), and preventing the exploitation of household support by commercial agents (tax system). The overlap between these two systems also implies balancing the perspectives of multiple stakeholders. Grid operators and energy service providers are concerned about the feasibility of a decentralised energy system, while public economists look at design principles of the tax system and the ensuing incentive structures (Wood et al., 2016). The considerations of the tax system are particularly important because many policy frameworks contain specific exemptions and support schemes to aid households in adopting microgeneration for the purpose of self-consumption (Moura & Brito, 2019).

For policy design, a key question is then how to treat "surplus" (European Commission, 2017): if prosumers feed in more energy than they consume, they are net producers and sell a (taxable) good. Many policy frameworks therefore set boundaries on prosumers' energy production through limits on plant size, surplus, or output thresholds (e.g., Campos et al., 2020; Clastres et al., 2019). While the incentive structures are well understood conceptually, there is little empirical evidence to date on how prosumers react to, circumvent or even undermine these limits.

Understanding the real-world consequences of prosumer policy is rendered both more complicated and more critical because the frameworks continue to evolve. In recent years, several countries have started to move away from feed-in tariffs and designed more complex structures and business models (European Environment Agency, 2022). Other countries still rely on feed-in-tariffs (e.g., Germany), but in parallel introduce different incentives through tax exemptions (Climate Action Network Europe, 2024). Different state actors are hard-pressed to design, implement, and adjust prosumer policy frameworks on the fly (e.g., Brown et al., 2019; Moura & Brito, 2019). Focusing on net metering and net billing schemes, countries like Poland and the Netherlands have also had to adapt their schemes and postpone transitions, after trial periods revealed problems with implementations or path dependencies with regard to other policy areas (see Maisch (2023) and Pilc (2023) for Poland; Van den Berg (2023) for the Netherlands). Spain is working with separate systems for prosumers with surplus and those without (Ministry for Ecological Transition, 2019). Austria entirely abandoned feed-in-tariffs and investment subsidies for private households and only exempts the installation of photovoltaic (PV) panels from value-added tax (Austrian Federal Chancellery, 2024). However, much of the current development has not yet been taken up and evaluated empirically in the scientific literature.

In this paper, we study the effects when information provision through digital tools meets prosumer regulation in a quasi-natural experiment in Croatia. Quasi-natural experiments arise from real-world settings where the outcome variable is systemically influenced by an external factor, similar to an experimental treatment, but the researcher can neither control the shape of the treatment nor which subjects are assigned to which treatment, as they could in a classic laboratory experiment (see Deschenes & Meng, 2018; DiNardo, 2010). This quasi-natural experiment came up during a field trial for smart metering because the regulatory context created an intervention case that was not deliberately directed by the researchers. Under the net billing system that was in force in Croatia during the study period in 2022–2023, prosumers' regulatory status depended on whether they produce more energy with their PV panels than they consume on an annual basis. If prosumers had a surplus at year-end, they were automatically re-classified to a financially less favourable regulatory status with larger administrative burden. Hence, under this policy, once prosumers realised with the aid of digital energy meters that they were approaching surplus, they were incentivised to cut any surplus, which in practice can be done in two ways: either to power down their PV plants, or to increase their consumption. Both options run counter to the core objectives of energy policy to promote microgeneration and reduce energy consumption. The paper builds on an ad-hoc research opportunity, where three aspects came together: (a) strong regulatory incentives, (b) metering feedback through digital tools, and (c) timing of data collection aligning with the regulatory deadline. The exploratory study provides a unique illustration of counter-policy effects, i.e., prosumer reactions to avoid unfavourable personal consequences that undermine the original intentions of the policy. Our research lies at the intersection of policy design in public economics and consumer research in the behavioural sciences. We connect these points in the following, discussing how these research strands address the interplay of regulatory incentives and prosumer reactions.

Theoretical background

To begin, there is a growing research body on the different models and designs for regulating prosumer markets. Moura and Brito (2019) coin the term "prosumer aggregation policy" in this context (p. 820). The term subsumes the different elements in the design of prosumer policy to give a name to the fragmented, heterogeneous policy landscape across different countries (European Environment Agency, 2022). However, the related literature looks at the policy design mainly from a high level. Conceptual studies consider how these heterogeneous settings can be systematically grouped (e.g., Burger & Luke, 2017), or discuss the integration of sub-segments of the prosumer market into the grid (e.g., Parag & Sovacool, 2016; Bothelho et al., 2022). These studies are complemented by techno-economic analyses and modelling studies that evaluate country-specific design options, for example, net metering (Brown et al., 2019), pricing schemes (Kuznetsova & Anjos, 2021), or net billing (Ordóñez et al., 2022).

These approaches leave two blind spots: First, how influential the incentives are for prosumers regarding *short-term* adjustments for compliance. Second, how information can *interact* with the regulation, as policy design studies typically do not address the capabilities prosumers need to comply with or circumvent the regulation. This resonates with the call in the energy transition literature to recognise the co-evolution of energy markets, technologies and policies: A purely techno-economic perspective on PV prosumers takes regulatory policy as an exogenous and static factor (Cherp et al., 2018). However, the actual policy effect results from the dynamic interactions between the PV technology, the prosumer actions and the regulatory structures they are embedded in (Markard et al., 2015). The overlap between the energy and the tax system in the prosumer context is one currently pressing example of the challenges identified in the conceptual literature on transition periods.

Extending from the broader background on prosumer policy, the specifics of the policy design are an important theoretical aspect that has been studied outside the prosumer context. Prosumer regulations often feature strict thresholds or cutoff values to prevent the over-utilization of generous policy support. These policy designs constitute what economists call a notch—i.e., a discrete jump in the tax treatment after crossing a threshold. For example, in the Croatian case, there is a status switch when prosumers have surplus (i.e., zero surplus is the threshold).

Current prosumer policies across Europe feature notches in the treatment of surplus (e.g., Spain), in the volume of electricity (e.g., France, Greece), and often also in PV size/capacity (e.g., Germany, Portugal) (Climate Action Network Europe, 2024). Crossing the threshold can have implications for a specific tax or regulation, or even delineate separate brackets of regulatory status (Climate Action Network Europe, 2024). With the recent advances regarding collective self-consumption, these policies are seeing adjustments and revision, while also new notches emerge regarding the geographical radius for self-consumption collectives (e.g., Portugal, France) (Solar Power Europe, 2023).

In public economics, it has long been recognised that notches create strong incentives to distort behaviour (for a review see Slemrod (2023)).[1] Empirical literature on various tax policies provides evidence that notches incentivize drastic reactions by market actors

[1] In the tax literature, notches are defined as "discontinuous jumps […] in the choice set of individuals and firms, because incremental changes in behavior cause discrete changes in net tax liability" (Slemrod, 2013, p. 260).

(e.g., Kleven & Wasseem, 2013; Hungerman, 2023; Best et al., 2020; Ito & Sallee, 2018; Slemrod et al., 2017). Moreover, there is a strong theoretical literature that shows that such distortions imply high economic costs from a welfare perspective (e.g., Conlon & Rao, 2020; Lockwood, 2020; Sallee & Slemrod, 2012; Slemrod, 2013). However, this knowledge on notches has not carried over to energy policy debates thus far (with the notable exception of fuel economy standards),[2] and to the best of our knowledge, the concept has not received any attention in the prosumer context.

Conversely, behavioural sciences have paid more attention to how consumers react to incentives, mostly without consideration of specific policy design aspects. In particular, the regulatory context may function as a cue that activates specific consumer attitudes related to costs and benefits (Steg et al., 2015). However, there is also evidence that energy (efficiency) policy can incentivise both intended and unintended behaviour (Jensen et al., 2015). The rebound literature discusses that behavioural responses to energy efficiency improvements may lead to undesired outcomes such as increased energy demand (e.g., Chitnis et al., 2014; Sorrell, 2007). However, the opposite of rebound effects can also be observed; for instance, sufficiency (i.e., reduction of energy consumption in the same area) or spillover effects (i.e., more awareness and reduction of emissions in other areas such as buying more biological, seasonal and regional products when grocery shopping; Nash et al., 2017). In the prosumer context, there is an argument for both rebounds and spillovers. Specific to PV installations and feedback, Luthander et al. (2015) argue that the microgeneration investment – coupled with information from HEMS – may lead to higher engagement and awareness, which can then encourage further energy savings. However, their review of studies on such behavioural adjustments concludes that the evidence is mixed and does not allow a clear causal interpretation (ibid.). On the flip side, there is emerging evidence of a "solar rebound" in the prosumer context (see the recent review by Dütschke et al. (2021)). Hence, it makes sense to consider the investment stage and the operational stage as two separate behavioural contexts. For prosumers with PV, the installation of PV is a one-time behaviour that does not necessarily affect the households' routines in daily life (Dütschke et al., 2021).

By contrast, feedback via digital metering tools, for instance by means of regular push notifications, may encourage households to optimize their energy consumption in everyday life. For example, feedback on household energy behaviour can be delivered through nudging, i.e., informational treatments that alter the decision framing without restricting the choice set (Cappa et al., 2020).[3] Using such feedback nudges and similar information treatments to guide behaviour is also appealing from a policy perspective due to the low cost of these interventions relative to price-based mechanisms (Andor & Fels, 2018). Making prosumers aware of their consumption level by means of smart meter feedback is among the strategies recommended to mitigate rebound (Font Vivanco et al., 2016).

Finally, the micro-level behaviour of a growing prosumer segment is increasingly coming under scrutiny regarding the aggregate effects on the energy system and the fairness of the support measures. Although energy policy generally encourages prosumerism, there are also reasons to constrain the economic incentives from a system perspective. Firstly, if a growing number of prosumers uses the grid as backup without limits, this creates problems with the recovery of grid costs and forces cross-subsidization by non-prosumers (e.g., Eid et al., 2014). Secondly, there is a risk that support policies intended for small-scale distributed generation are exploited for commercial purposes and have unintended distributional effects (e.g., Pienkowski, 2021; Kubli, 2018). The latter is complicated by legal cases challenging whether specific prosumer policies and activities are consistent with broader tax concepts.[4] These considerations are particularly important as behavioural interventions are increasingly discussed as part of broader policy packages, despite limited evidence for their efficacy as a standalone intervention (Nisa et al., 2019).

[2] There is a group of papers studying notches in fuel economy, which is contained within the automobile context. Notable examples include Sallee and Slemrod (2012), Ito and Sallee (2018), Konishi and Managi (2020).

[3] The concept of nudging was developed by Thaler & Sunstein (2008) under an originally more specific definition, but has proliferated since gaining momentum in policy discourses.

[4] See the landmark case regarding the value-added tax rules applied to rooftop PV in Hall (2013), legal reference: https://curia.europa.eu/juris/document/document.jsf?docid=138693&doclang=EN

Contribution and outline

Taken together, the literature indicates that regulatory design, information, and prosumer behaviour intersect but are still studied in isolation by scholars in public economics, consumer research, and engineering. However, policymakers in many countries currently formulate or revise regulatory frameworks for prosumers and face substantial challenges when trying to reconcile these aspects in drafting and implementing legislation.

The data collected in the present Croatian quasi-natural experiment provide unique empirical insights into the real-world micro-level effects of mis-aligned prosumer regulation. We combine survey and smart meter data, collected both before and after a policy notch, to show how feedback from digital tools enabled prosumers to react to the policy design, resulting in unintended consequences – increasing consumption, reducing production, and even drastic reactions such as voluntarily shutting down microgeneration.

Thereby, we identify an understudied interplay between policy instruments that could be either an opportunity or a costly oversight. This provides highly policy-relevant and timely evidence for shaping prosumer policies and for avoiding adverse impacts of policy notches. We believe that the experience and example of Croatia can serve as an alert for other countries and their respective policies. As this study builds on an ad-hoc research opportunity, it was not pre-registered and should be considered exploratory.

The paper is organized as follows. Case study section describes the context of the Croatian case study and details the prosumer regulatory framework in place. Method section contains the methodology: the data collection, sample structure and analytical strategy. Results section gives the results from the survey and smart meter data in chronological order. These results are discussed in Discussion section, and Conclusion section concludes the paper.

Case study

Policy framework

From 2021 until the end of 2023, the Croatian legal framework for prosumers consisted of two distinct regulatory models: the "Self-Consumption" model which applied to households and public institutions, and the "Final Customer with Own Production" model, which encompassed all other customer categories, but can also include households (Parliament of Croatia, 2021, Article 51). These models were established by the Law on Renewable Energy Sources and High-Efficiency Cogeneration, Article 51 and applied until the Amendment in 2023 (Parliament of Croatia, 2021, 2023). Under this law, for household PV systems, a household transitioned to the "Final Customer with Own Production" model if they exported more energy to the grid than they imported in a given year. Under this billing approach, surplus energy not self-consumed on-site is bought by suppliers at a minimum of 90% of the user's average electricity price.[5] Unlike the "Self-Consumption" model, which allows netting within a month, this model does not offer any netting. Additionally, the status switch comes with increased compliance burden that also makes it undesirable from a non-monetary perspective.

Assignment to the two models is not an option for the prosumers. Instead, the classification is based on the annual surplus, so each prosumer's status is determined by the regulator at the end of the calendar year. Surplus in the regulation is defined as grid-in minus grid-out, i.e., the difference between energy taken from the grid and energy returned to the grid, for instance due to PV production (Parliament of Croatia, 2021). This binary status classification in the Croatian regulation creates the policy *notch*: a discrete status switch for any prosumer with surplus greater than zero at the end of the calendar year.[6]

In practice, the policy leaves prosumers two margins of adjustment to avoid a status switch: increase energy consumption (i.e., increase grid-in) or reduce the PV plants' production (i.e., decrease grid-out).

[5] The average final household electricity price in Croatia by the end of 2022 was 10.6 €-cents / kWh (Eurostat, 2023). However, this masks considerable heterogeneity across billing codes, energy suppliers and sub-national entities, with the *pre-tax* prices on which the 90% remuneration is calculated range from 0.037 to 0.074 €-cents / kwh and then taxes are levied accordingly (see Zelena Energetska Zadruga, 2023).

[6] The system described above was in place during the entire study period. Recently, amendments to the Law on the Electricity Market and Renewable Energy Sources were accepted in July 2023 (Parliament of Croatia, 2023). The transitional period starting in 2024 allows prosumers to retain the simpler regulatory model, and the ministry aims to formulate a new system by March 31, 2025, initiating its application on January 1, 2026 (HEP, 2023a).

Table 1 Exemplary comparison of regulatory status models and total savings for 6 kWp rooftop PV

	Self-Consumption Model	Final Customer with Own Production
Total annual production	7,200 kWh	7,200 kWh
Direct savings	315 EUR assuming that 30% of the produced energy is consumed during production	315 EUR assuming that 30% of the produced energy is consumed during production
Savings due to net metering	525 EUR	Not applicable
Savings due to excess production and financial settlement	63 EUR Shown on the bill as a monetary credit that accumulates every month and is used during months with less production	267 EUR The supplier pays based on the bills issued each month. As of 1.1.2023 this is tax-exempt up to 1,327 EUR (10,000 Croatian Kuna)
Total savings in one year	903 EUR	582 EUR

Accordingly, those are the two main hypotheses for the empirical analysis.

Economic incentives

To underscore how strong the regulatory incentives are to avoid a status switch, Table 1 presents a comparative analysis of the economic outcomes associated with the two models of PV system ownership: the Self-Consumption Model and the Final Customer with Own Production Model. The presented figures are not empirical results, but show the economic considerations that are at the *foundation* of our results. The table delineates the annual electricity production, direct savings, and additional financial benefits associated with each model, based on the exemplary case of uniform annual production of 7,200 kWh. The calculations are based on the experience of the implementation partner Zelena Energetska Zadruga (ZEZ)[7]with publicly available references in the national language from the energy provider Hrvatska elektroprivreda (HEP), see HEP (2023a, b).

For the purpose of calculating the Return on Investment (ROI),[8] the following assumptions are posited:

- The initial cost per installed kilowatt-peak (kWp) is 1,327 EUR, yielding a total investment of 7,962 EUR for a 6 kWp system.
- Operational and maintenance costs, subsidies, or incentives are not factored into the simplified ROI calculation.
- The operational lifespan of the system is projected at 25 years.
- Electricity price fluctuations and discount rates are not incorporated.

Over 25 years, without discounting for the time value of money, the total returns aggregate to 22,575 EUR for the Self-Consumption Model, but only 14,550 EUR for the Final Customer Model. This yields an ROI of approximately 183.53% and a payback period of 8.82 years for the Self-Consumption model, compared to 82.74% ROI and 13.68 years payback period for the Final Customer model.[9]

Both the payback period and the ROI indicate that rooftop PV is economically viable under both options in Croatia, hence the adoption decision should not be affected. However, the relative profitability is much higher for the Self-Consumption model (than the Final Customer model), and this incentivizes behavioural adjustment to avoid the status switch from self-consumption to own production. The consequence is an economic incentive to adjust behaviour during the operational phase of the asset. In this context, it should be noted that the dimensioning of the plant at the investment stage is a key determinant of whether or not a household is at risk of running a surplus (cf. European Climate Initiative, 2021).

[7] ZEZ is an energy cooperative operating in Croatia, see the company's website: https://www.zez.coop/en/

[8] Total Returns = Annual Savings × Lifespan of the System. The ROI is derived using the formula:

$$ROI = \frac{Total\ Returns - Initial\ Investment}{Initial\ investment} \times 100\%$$

[9] The payback period is the time it takes to recoup the investment, i.e., initial investment divided by annual savings.

From an economic perspective, the above calculations pre-suppose that prosumers who have perfect information and perfect control over their surplus will avoid a status switch. This was not the case at the beginning of the study period and this critical aspect of information provision is therefore explained in the following.

Intervention through information

The main change in information provision came through the *Sunči* mobile app developed by ZEZ that was tested in a field trial as part of the Horizon 2020 project NUDGE that ran from 2021 to 2023 (see Data collection section for details on data collection). The app was available from early 2022, and provided consumers with a new tool to track and monitor energy consumption variables. The target group for the app in this initial phase were prosumer households who had self-selected into participation in the field trial and received the app as part of this (see Sample section for details on the sample).

In November 2022, a feedback nudge intervention was implemented. The intervention was designed to provide participants with timely information regarding their energy consumption. As part of this intervention, specific pages regarding the surplus were added in the app. This offered an overview of the aggregated consumption and production amount that was relevant for the regulatory assignment, including accumulated values on a monthly and annual basis. This information was displayed on a separate page in the app (*Podaci* page, see Figure 7 in Appendix A).

The intervention was a major improvement in the transparency relative to the status-quo ante. Previously, the information accessible to end consumers was characterised by inflexibility and limited scope. Prosumers were equipped to monitor their aggregate energy production via the PV inverter application, yet they lacked detailed insights into the specific proportions of energy self-consumed and fed back into the grid. The only available comprehensive data regarding energy consumption and grid return were presented in totalized formats within monthly billing statements, resulting in a retrospective and aggregated understanding of energy interaction. Additionally, the distributors' portal offered a more granular view of energy consumption, delineated in 15-min intervals, but this was provided also with a near-monthly lag in data availability.

Based on personal feedback of involved households to ZEZ during the field trial's stakeholder events, the app provided prosumers with the capability to track not only their total energy production, but also their consumption, self-consumption, and the volume of energy returned to the grid, all in a real-time context. The shift from delayed billing information to comprehensive and immediate access to data improved the prosumers' ability to comprehend and modify their consumption patterns. As a secondary effect, the advance in transparency enabled prosumers to more effectively navigate the regulatory landscape and optimize their energy practices in alignment with the economic incentives of the Self-Consumption model.

Method

Data collection

The data were collected as part of the Horizon 2020 project NUDGE. The main aim of the project was to study nudging, i.e., non-monetary incentives altering a subject's choice architecture, through the medium of an online application.[10] Within the project, ethical guidelines have been developed to comply with the standards for European research projects including the General Data Protection Regulation. Hence, before data collection, all participants were informed about the aim of data collection, the use of their data, anonymity and potential benefits and risks. All participants agreed to the data collection (for survey and smart meter data) beforehand.

To analyse the behavioural reaction, we use two data types: survey and smart meter data. We conducted two online surveys – one running end of October 2022 to mid-December 2022 and another one in April 2023. The surveys cover both socio-demographic and energy-related questions. Specifically, our analysis focuses on (i) behaviour regarding the regulatory status (e.g., shut down PV plant, turn on other electricity appliances, change the heating system), (ii) the self-assessed energy consciousness of

[10] See the project website: https://www.nudgeproject.eu/. Further information on the field trial is presented in Appendix A.

the participants, and (iii) electricity consumption and self-consumption (intention and future behaviour). For the analysis of the policy effects, we use smart meter data from the period from 1 June 2022 to 28 February 2023. The high-frequency data are aggregated to daily values and focus on two outcome variables. Production is the energy generated by the rooftop PV. Consumption is total household consumption, including self-consumption and energy drawn from the grid. All values are reported in Wh summed over a 24-h period. Summary statistics are presented in Appendix A, Table 4.

Sample

The sample consisted of 82 participating households with rooftop PV in three cities in Croatia: Zagreb, Osijek, and Varaždin that were recruited by ZEZ.The average installed PV capacity was 5.5 kWp with a standard deviation of 2.5 kWp. All households were equipped with smart metering, and they received information about their PV production, self-consumption and overall energy consumption through the *Sunči* mobile app (see Intervention through information) section.

Not all 82 participating households completed the survey, leaving us with 54 responses from households in the first online survey and 80 participating households in the second survey.[11] For describing the sociodemographic composition of the sample, we refer to the second survey, since it covers 80 out of 82 participants. The sample consisted mainly of men (93%) and six female participants (7%) aged between 32 and 73 years ($M_{age}=48$ years, $SD=12.35$). All survey respondents owned their home (84% single-family detached houses) and had a PV panel installed as a pre-requisite for participation. The average household of the responding participants consisted of two adults aged between 20 and 64 years and one child under the age of 14 living in a home with 172m2 (living space ranging from 64 to 630m2).

The sample represents households whose housing conditions allowed them to optimize their consumption with self-generated electricity. This included owning flexible household appliances and living in larger homes (Croatian average size of housing unit 74.4 m2).[12] 30% of the participants owned electric heating appliances for space and water heating (respectively), 12% air conditioning, 7% an electric vehicle or a swimming pool. The sample consisted of more families with children than the Croatian average (27%). It is debatable whether this household composition favours an increase in self-consumption (e.g., due to more consumption to shift) or restricts it (e.g., due to daily routine with children). By contrast, the average age and the share of homeowners in the sample were similar to the Croatian average (average age 43 years, 71% homeowners).

Strategy for data analysis

We provide a descriptive analysis of the data that is motivated by the small sample and the expected heterogeneity in the individual reactions. The results are organised chronologically. We begin with the first survey wave to examine the prosumers awareness and intention with regard to the policy. Second, we compare these self-reported adjustments to the smart meter data. We first look at the full sample, and subsequently choose 10 participants for case studies on the individual behavioural reaction in a time-series plot.[13] The results conclude with the final survey wave and a comparison across waves. Most questions are congruent across the survey waves, but we added questions on ex-post experiences in the final wave.

Unfortunately, not all participants answered each survey wave, and there were data transmission problems with some participants in the smart meter data. This leaves a discrepancy between the survey sample and the smart meter sample. We do not want to restrict the sample any further given the limited sample and proceed with all survey respondents in each wave. We then examine each participant's smart meter data and select prototypical cases for each type of reaction. The analysis sample is therefore inconsistent across the data types, but this was a conscious

[11] We attribute the lower participation in the first survey to technical delays in the early phase of the project. At the time of this survey wave, recruitment was still ongoing and the number of participants increased over time. For details, see Deliverable D2.3 in NUDGE (2023).

[12] All reference numbers are based on Croatian Census from 2021 (Croatian Bureau of Statistics, 2021).

[13] None of the households selected as case studies underwent any changes in their living situation that could be confounded with their observed changes in electricity production and consumption.

Table 2 Descriptive statistics for survey wave 1 and 2 on policy-related behaviour

	Survey wave 1 (*n* = 54)			Survey wave 2 (*n* = 80)		
Self-consumption -2 = decreased a lot, 2 = increased a lot	M (SD) = 0.53 (0.94) (*n* = 49)	Min, Max = -2, 2 (range = -2, 2)	"I am not sure": 6% (n = 5)	M (SD) = 0.38 (0.97) (n = 78)	Min, Max = -2, 2 (range = -2, 2)	"I am not sure": 2% (n = 2)
Turning on additional electrical appliances	Yes: 61% (n = 33)	No: 26% (n = 17)	Other: 13% (n = 7)	Yes: 63% (n = 50)	No: 23% (n = 18)	Other: 15% (n = 12)
Shutting down the PV plant	Yes: 44% (n = 24)	No: 41% (n = 22)	Other: 15% (n = 8)	Yes: 43% (n = 34)	No: 50% (n = 40)	Other: 8% (n = 6)

choice to give comprehensive insights on the policy given the data constraints.

We discuss five prototypical reactions to the regulatory policy, illustrating each reaction with the production and consumption patterns of two exemplary participants as case studies. Considering the very diverging reactions and small initial sample, we only focused on those participants where the reaction is tied to the intervention timing, in order to avoid spurious correlations. The figures in Results from smart meter data on prototypical reactions section give electricity produced by the participant's PV panel and electricity consumed by the participant (provided from the PV panel or from the grid) in kWh. Metered daily averages are converted to seven-day rolling means in order to correct for variance from weather conditions, household events or similar. Color-coding distinguishes the different phases: Blue for pre-intervention, black during intervention, red after intervention and green for the new calendar year of 2023. As the timing of the intervention varies between participants, vertical dashed lines indicate when the intervention took place for the respective participant. Additional information from the survey data is used to interpret the observed production and consumption trends in each case study participant. There are several other participants with similar time series plots in the overall sample, while for other households there are only weak tendencies, which does not allow proper categorization. We selected two cases for each type to characterize the range of identified reactions and underscore the heterogeneity. These serve as illustrative examples of the scope of reactions in the sample. For transparency, figures on the other participants are included in Appendix B, with a categorization into the five prototypical reactions.

Results

Results from survey wave 1 on policy-related behaviour

Participants were asked to report their policy-related behaviour by implementing five variables (all single items). Specifically, we asked participants about (1) their self-consumption, (2) whether they turned on additional appliances to buffer PV over-production, and (3) whether they shut down the PV plant to avoid the status change. Only in wave 2, we asked (4) whether participants changed their heating system, as heat pumps or electrical radiators may increase electricity consumption, and (5) whether their regulatory status actually changed in 2023. The descriptive statistics for the common questions in both waves are displayed in Table 2.

During fall 2022 (wave 1), the results indicate no or only a little increase of self-reported PV energy use. This is out of line with the initial objective of the app to encourage self-consumption. By contrast, most participants reported to turn on additional electrical appliances during hours of high PV generation. This serves both a direct financial benefit and the alignment of consumption patterns to the regulatory incentive. The survey also reveals high awareness of the policy. Almost half of the participants considered shutting down their production, and only 15% did not have a clear opinion. In this context, it is noteworthy that the dimensioning of the PV plant during installation is a key determinant on whether participants will be at risk of running a surplus, so it is not surprising that a substantial fraction answered "No". The category *Other* includes the option "I did not think about

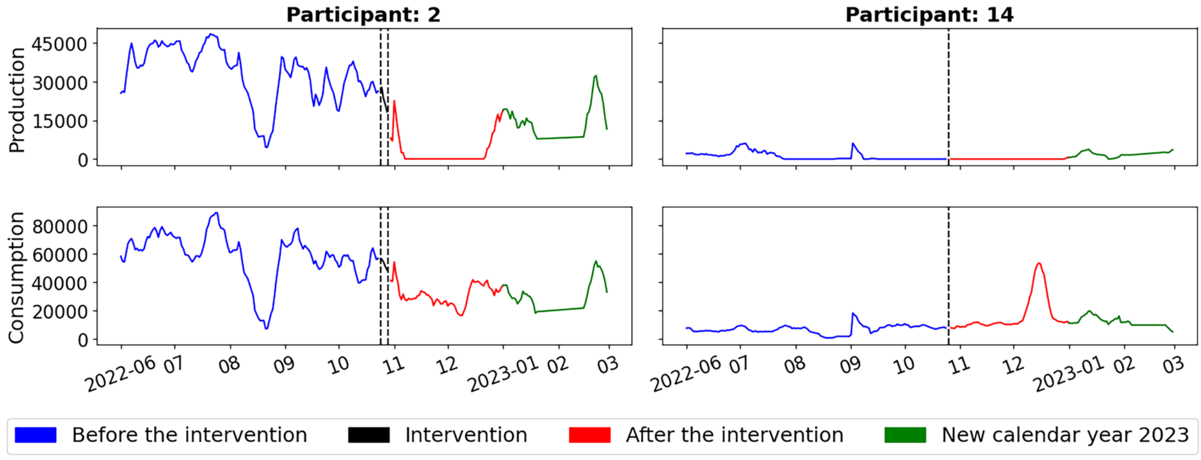

Fig. 1 Temporary shutdown of the PV plant until year-end

it" to distinguish. The sample is quite evenly split on whether they consider self-curtailment or not, indicating that the policy creates segmentation depending on the households' PV installation and equipment.

Results from smart meter data on prototypical reactions

For each of the five prototypical reactions, we present the two case studies illustrating heterogeneity side-by-side. The dashed lines indicate the intervention start (i.e., receiving access to the feedback app; double line if activation occurred over two days), and the break from red to green marks the end of the year.

Temporary shutdown of the PV plant until year-end. Participants 2 and 14, as can be seen from the drop in the red production line, temporarily shut down their PV system, a step they had mentioned in the survey. During the shutdown, participant 2 strived to increase electricity consumption by installing an electric boiler to substitute for gas in hot water heating and by switching on additional appliances at times when the PV system produced more electricity than the household could consume. Participant 2 also strongly disagreed that they had made any attempts to save electricity at home in the months after the intervention. By contrast, participant 14 shut down PV production and maintained consumption as before (apart from a short peak towards year-end). In both survey waves, participant 14 emphasised that they intended to and tried to save electricity at home; moreover, they did not switch on any extra electrical appliances when the power plant was producing much more electricity. These responses stated by participant 14 do not correspond with their smart meter data; however, electricity saving efforts might have been levelled out by participant 14's low overall consumption level. Eventually, in 2023, participant 14 received the "Self-Consumption" status (Figs. 1, 2, 3, 4, and 5).

Increase consumption until year-end. Participants 19 and 43 showed a steep incline in electricity consumption immediately after the intervention, whereas their production remained unchanged or even decreased. After the turn of the year, their consumption returned to previous levels. Both participants expressed a strong intention to increase their own PV electricity consumption and strongly disagreed with trying to save more electricity at home in the three months following the intervention. They reported that they frequently used appliances when production exceeded consumption, with participant 19 using a washing machine, heat pump and clothes dryer, and participant 43 using air conditioning and electric heaters. Participant 43 explicitly stated that they did not consider the above reaction of shutting down the PV system temporarily, but instead decided to increase their consumption in order to balance their overall production-consumption ratio.

Decrease consumption and maintain beyond year-end. Participants 38 and 40 exemplified a persistent reduction in electricity consumption beyond the turn of the year. Participant 38 stopped using the electric boiler and opted for winter mode, i.e., a switch to an alternative heating method during the cold season. Both participants dismissed the option of turning on additional devices when production exceeded consumption; participant 40 even rejected this notion strongly. The electricity saving efforts of participants 38 and 40 as observed in the smart meter data were consistent with their survey responses: both intended to save more electricity and use more PV energy after the intervention; both stated that saving energy made them feel good; and both described themselves as rather energy-aware households.

Decrease consumption but bounce back with the new year. Participants 46 and 48 decreased or at least maintained their electricity consumption after the intervention, but by the turn of the year, their consumption increased remarkably, even exceeding their previous levels and partly mirroring their production pattern. At the time of the intervention, participants 46 and 48 stated strong intentions for saving electricity in the next three months, but rather for reducing energy costs than for avoiding feelings of guilt. At the subsequent survey, participant 48 had abandoned their intentions for further saving energy. Both participants aimed for self-consuming more PV electricity instead and leveraging eventual production surplus; to

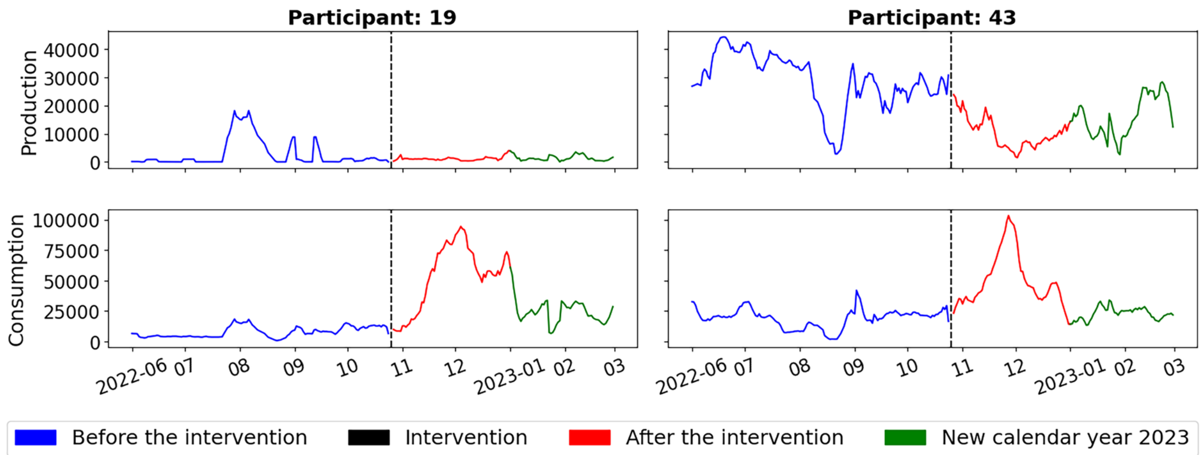

Fig. 2 Increase consumption until year-end

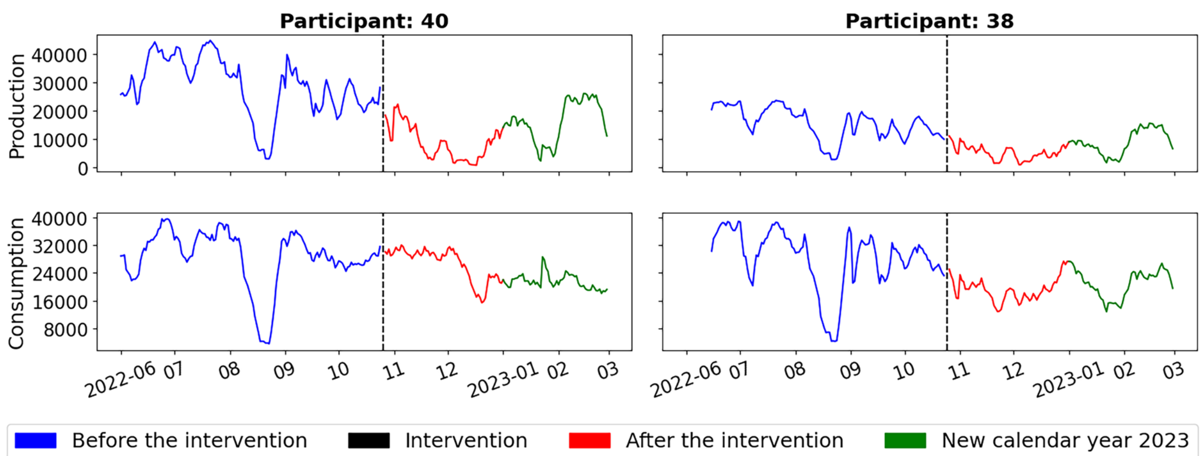

Fig. 3 Decrease consumption and maintain beyond year-end

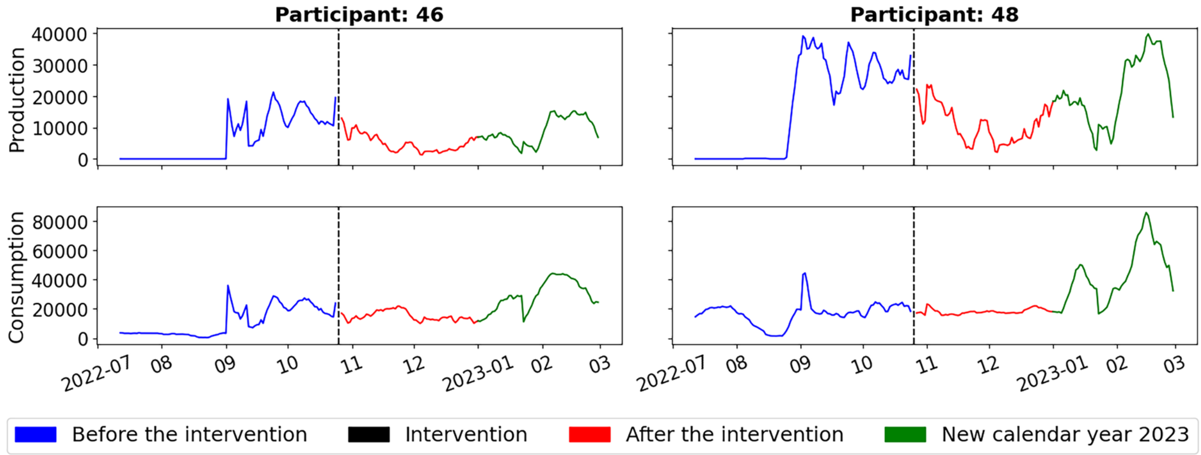

Fig. 4 Decrease consumption but bounce back with the new year

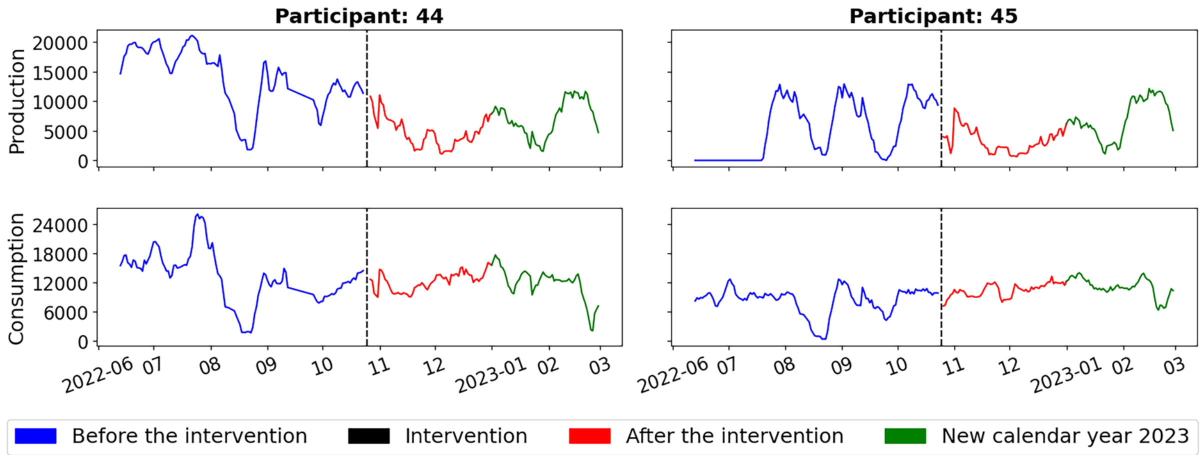

Fig. 5 No visible reaction during the intervention period

this end, participant 46 planned to use less gas and to charge an electric vehicle, and to consequently reduce carbon emissions.

No reaction. Participants 44 and 45 served as examples for a lack of visible reaction to the policy. This does not ascertain that they were not aware; random fluctuations in production and consumption might mask subtle underlying reactions. Both participants did not commit to electricity saving intentions or attitudes in either survey: They neither agreed nor disagreed with the statement on guilt about not saving energy. At the time of the intervention, they neither agreed nor disagreed with statements on trying to save or having already saved electricity. Participant 44 stated neutral intentions towards saving electricity in the three months after the intervention. Both participants replied "I am not sure" in their self-assessment whether their carbon emissions had decreased in the last three months.

Results from ex-post survey analysis

In spring 2023, we asked participants in a second survey wave the same questions as in survey wave 1 to assess potential differences and provide a policy evaluation.

Results from survey wave 2

For the self-curtailment behaviour, the descriptive statistics for survey wave 2 show that participants perceive their self-consumption to be unchanged or increased a little over the first quarter of 2023 (see Table 2). Even in the spring, a large proportion of the participants (43%) stated that they considered shutting down the PV plant to avoid the status change. Moreover, the majority (61%) reported to have turned on additional appliances to achieve savings despite the over-production of their PV power plant. Similarly, only 28% of participants in wave 2 stated to have *not* changed their heating system. 50% ($n=40$) reported that they started to occasionally heat with electricity (air conditioner or electricity heaters), 14% ($n=11$) reported to use a heat pump since the installation of the PV plant, 5% ($n=4$) replaced the gas boiler with an electric one, and 4% ($n=3$) chose "Other". These results fit with the other self-curtailment variables and indicate an increase in electricity consumption by most participants after the installation of the PV plant, which may lead to rebound effects that are incentivized by the policy.

Notably, the responses for increasing consumption and shutting down the plant from the second survey wave are on par with those from the fall in the first survey wave. Applying a paired t-test as an inference statistical comparison of the self-consumption variable (with $n=48$) shows no significant difference (assessed against p-value < 0.05). However, the small sample size may limit the comparative analysis, as suggested by a power analysis. For a two-tailed paired t-test, power beta = 0.80, alpha = 0.05, we would only detect small to medium effects of d = 0.45 with the given sample size. Examining the cross-tables (therein excluding participants who did not answer the same question in both surveys), it emerges descriptively that only eleven out of 43 participants (26%) changed their answers across time regarding the shut-down of their PV plant (from yes to no or vice versa). The same pattern results for the question to turn on an additional appliance: 12 out of 44 participants (27%) changed their response between survey wave 1 and survey wave 2.

Finally, in survey wave 2, we asked whether participants' status had changed at year-end and why (question is omitted from table, multi-response was possible). Only three participants (4%) experienced a status change – one participant reported having over-dimensioned the plant in the installation, the others attributed the status change to not using the PV plant enough. The most common response (46%, $n=37$) was that participants stated they avoided the switch thanks to the correct dimensioning of their plant. The distribution of responses fits with the smart meter data, where not all individual participants show strong reactions, but those that react do so drastically. While 9% ($n=7$) of participants reported that they had actually engaged in self-curtailment (turned off PV plant), 19% ($n=15$) reported that changing the heating source to electricity helped them avoid the switch. 4% ($n=3$) reported to have bought an electric vehicle to use the PV-produced electricity.

Before-after comparison of electricity consumption questions

In both survey waves in fall 2022 and spring 2023, we also asked participants about their electricity consumption behaviour. Specifically, for the electricity consumption and their PV self-consumption, we implemented questions on the intention to save electricity (three items, Cronbach's alpha = 0.92 and 0.90, in wave 1 and 2 respectively) and the intention to use more PV energy (three items, Cronbach's alpha = 0.90 and 0.93), as well as their expected increase in electricity consumption and self-consumption (one item each). For interpreting the scale values, for all variables, higher values indicate a higher energy consciousness, a higher intention and an expectation of higher (self-)consumption. The descriptive statistics of these variables as well as the internal consistency based on Cronbach's alpha and their correlations for both waves are displayed in Table 3.

To compare the outlined survey variables across waves, we conducted paired t-tests with Bonferroni correction (one t-test for each variable) with the responses of the 54 households who participated in both waves. The results (means and t-tests) are presented in Fig. 6. Participants had a high starting motivation (above mid-scale in wave 1). When conducting the paired t-tests for the electricity behaviour variables between waves (with $n=54$), none of the five t-tests reaches the statistical level of significance (all p-values > 0.05). Thus, none of the described variables changed significantly over time. However, descriptively, we observe a trend over time in an

Table 3 Descriptive statistics, correlations and internal consistency (Cronbach's alpha on the diagonal) for key variables of survey waves 1 (upper part) and survey wave 2 (lower part) on electricity consumption behaviour

Survey wave 1 ($n=54$)	M (SD)	Min, Max (range)	1	2	3	4	5
1 Self-assessed energy consciousness	7.24 (1.32)	5, 9 (1, 9)	–- (single item)	-0.17	-0.07	-0.00	-0.02
2 Intention for electricity saving (electricity consumption)	3.56 (1.08)	1, 5 (1, 5)		0.92 (three times)	0.62 ***	-0.14	-0.19
3 Intention for PV energy use (self-consumption)	3.83 (1.10)	1, 5 (1, 5)			0.90 (three items)	-0.12	-0.11
4 Expected increase in electricity consumption	1.48 (2.44)	-4, 4 (-4, 4)				–- (single item)	0.84 ***
5 Expected increase in PV self-consumption	1.50 (2.15)	-4, 4 (-4, 4)					–- (single item)
Survey wave 2 ($n=80$)	**M (SD)**	**Min, Max (range)**	**1**	**2**	**3**	**4**	**5**
1 Self-assessed energy consciousness	7.34 (1.25)	4, 9 (1, 9)	–- (single item)	0.25 *	0.21	-0.10	-0.08
2 Intention for electricity saving (electricity consumption)	3.60 (0.99)	1, 5 (1, 5)		0.90 (three items)	0.66 ***	-0.16	-0.04
3 Intention for PV energy use (self-consumption)	3.85 (0.98)	1, 5 (1, 5)			0.93 (three items)	-0.05	0.03
4 Expected increase in electricity consumption	0.69 (2.43)	-4, 4 (-4, 4)				–- (single item)	0.71 ***
5 Expected increase in PV self-consumption	1.23 (2.30)	-4, 4 (-4, 4)					–- (single item)

*p-value <0.05, ***p-value <0.001

electricity-conscious positive direction. There is a slight increase in the intention to save electricity and to use more self-produced electricity. The energy consciousness increases slightly on average. There is a decrease both in the mean for expected increase in electricity consumption and in the expected PV self-consumption. The latter is not in line with the other descriptive trends. We also examined the correlations within each wave (see also Table 3) and found positive correlations between the intention to save electricity and the intention to use PV energy (wave 1: $r=0.62$, p-value <0.001 and wave 2: $r=0.66$, p-value <0.001), and between the expected increase of consumption and self-consumption (wave 1: $r=0.84$,

p-value < 0.001 and wave 2: $r = 0.71$, p-value < 0.001). In wave 2, the self-assessed energy consciousness and the intention to save electricity have a small, positive correlation ($r = 0.25$, p-value = 0.028). All other correlations were not significant. Overall, there is no strong evidence for a significant effect of the policy on the underlying electricity consumption behaviour. We take this as indicative of a disconnect between short-term adjustment and long-term behavioural change. However, we acknowledge that the small sample size limits statistical inference and constrains the external validity of the results.

Discussion

This study has exploited a quasi-natural experiment among Croatian households with rooftop PV that enables the empirical evaluation of how prosumers react to regulatory incentives. The policy context we explore provided strong economic incentives to reduce surplus, which was made transparent with metering feedback through a digital tool. Prosumers' behavioural reactions revealed the interplay between rigid regulatory frameworks and information measures aimed at consumer awareness. Our study depicts an example where these two approaches intersected. Importantly, it is only through this intersection that we observe substantial changes in behaviour. The policy *notch* in the Croatian regulatory framework provided strong economic incentives to adjust production and consumption. The *information feedback* subsequently made prosumers aware of their status at a crucial point in the timeline (end-of-year). The result is a swift and drastic reaction by those participants that had thus far underutilized their production. In order to avoid the status switch, prosumers increased energy consumption and curtailed production as

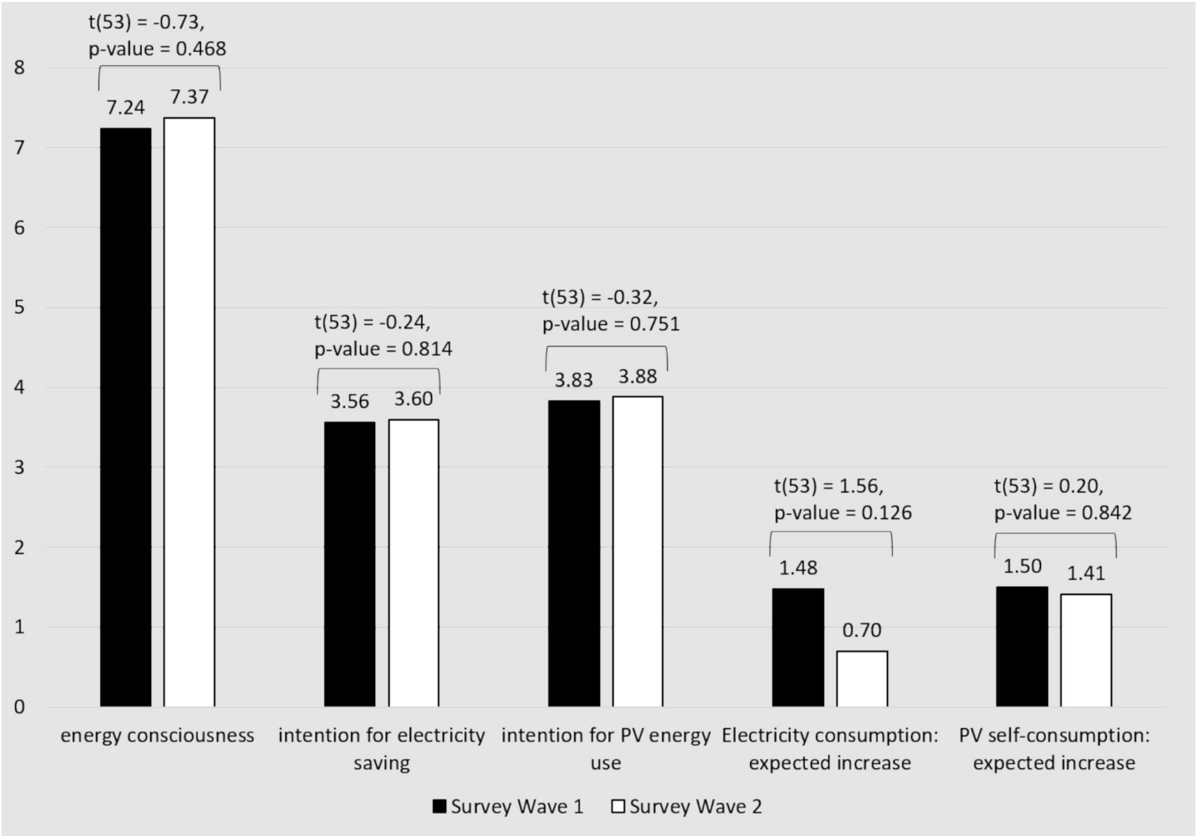

Fig. 6 Results of the comparison across survey waves for 54 Croatian prosumer households participating in both survey waves, displaying means and paired t-tests with p-values

hypothesized.[14] In the following, we discuss the results and put each main finding into context with the limitations and implications that pertain to it.

Study design

We demonstrate the interdependence between metering feedback, timely information provision and regulatory incentives in the course of a quasi-natural experiment that was not specifically designed for this purpose. This presents both a limitation and an opportunity. The sample size limits our analysis in terms of methodology and scope. Therefore, we illustrate the short-term adjustments that can be directly related to the timing of the feedback intervention only for those participants where additional information is provided by the app. The survey included questions related to the policy, but originally focused on other energy-related issues. In addition, the experiment structure mixes the information and the regulatory components without the possibility to disentangle the relative contributions of these factors.

Nevertheless, the setting was also a unique research opportunity. Without the co-incidence of the three elements described (incentives, feedback, timing), there would not be evidence to identify the policy impact. The process of this study followed the sequence of data collection, rather than an ex-ante experiment design. Yet, it is hard to conceive how such an experiment could have been designed purposefully considering the research fields and literature strands that intersect here.

The argument we build is that the prosumer reactions were a direct consequence of the regulation. Considering the ad-hoc opportunity and the lack of a counterfactual, our methodology is admittedly unusual for delivering causal effects. Our methodological advantage, however, is the combination of smart meter and survey data. In the survey, prosumers revealed not only their awareness, but also confirmed the reactions observed in the smart meter data. The second strong point is the timing of the reactions. Hence, we believe that we are likely to *understate* the extent of the reaction: our approach only picks up on those prosumers who took action directly after the new information became available. Prosumers who were smoothing consumption and production throughout the year, or made marginal adjustments to a small surplus are classified as 'No Reaction' in our approach. Only strong *and* timely reactions are categorized, the most drastic of which is curtailment, for which we see no other plausible explanation and which is supported both by smart meter and survey data.

Prosumer reactions

Among the reactions we identify, the voluntary curtailment is particularly concerning. The counter-policy measures taken by households are not only inefficient, but can reduce renewable generation potential at a system level, if this reaction is widespread in the prosumer population. For the increases in energy consumption, there is mis-alignment with energy-saving targets, but the picture is more nuanced. Those consumers who employed additional electronic appliances to shift their load profile record higher energy consumption. This fits with the literature on rebound effects (e.g., Dütschke et al., 2021; Reimers et al., 2021). Yet in our case, this rebound is induced specifically by the policy.

We are not aware of empirical evidence for these "policy-induced rebound effects" for prosumer energy consumption. However, there are also cases where the evidence supports an unintended *positive* side effect of the policy that may lead to increased technology adoption, as the survey responses indicate acquisition of heatpumps and even electric cars to use more of the produced solar energy. We certainly do not claim that a wider technology diffusion is causally tied to the regulation, but the correlation is nevertheless highly relevant for sector-coupling and can be characterized as a spillover effect (see Galizzi & Whitmarsh, 2019). In fact, for the common mechanism of adjusting heating mode, the reactions *within* the cluster encompass strategies with different energy profiles, i.e., heatpumps vs. heating with air conditioners. In either case, it is questionable whether such decisions should be made ad hoc to avoid surplus, rather than selected and sized according to long-term investment planning.

In order to avoid the status switch, prosumers did not simply increase energy consumption or curtail production: there is more heterogeneity in the observed reactions than expected. Prosumers differed in their reaction in the smart meter data, which is also reflected in the distribution of self-reported reaction

[14] Although the reactions are more heterogeneous, we first focus on these two prototypical reactions due to their inherent conflict with the broader prosumer policy objectives.

strategies in the survey. Taken together, this suggests that there is no one-size-fits-all adjustment, as the individual behavioural reactions are influenced by technical equipment. The heterogeneity observation can be seen as another clear link to the notches literature. Sallee and Slemrod (2012) emphasize that part of the welfare costs of notches come from heterogeneous incentives and compliance requirements in the distribution. Our results document such heterogeneity ex-post for prosumer reactions in a very different context.

However, a large fraction of prosumers avoided any repercussions because their PV plant was correctly sized. Policy discussions indicate that the incentive to "right-size" PV was in fact intended (European Climate Initiative, 2021; Budin et al., 2023). There are two points to make from this link between the investment and the operational stage. Firstly, sizing can explain the reaction of those households that decreased energy consumption or showed no visible reaction. When the notch in the regulation is not relevant or binding, the participants could react to the feedback intervention alone that encouraged decreases in energy consumption. The quasi-natural experiment (from regulation) and the original field experiment (through nudging) were setting conflicting incentives regarding energy consumption behaviour, which can provide an explanation for the heterogeneity. Secondly, the PV sizing effect puts importance to the path dependency from the pre-ceding investment decision, where prosumers pre-determine which regulations they need to comply with and which economic incentives they may expect. By extension, the right-sizing aspect is related to the *pre*-bound effect, which suggests that households may consume less energy than indicated by their building's energy rating that is imposed, for instance through labelling regulations (Sunikka-Blank & Galvin, 2012). The findings thus have implications both for the use of behavioural interventions providing information, and for the design for prosumer regulation.

Transparency through information

In the Croatian case, the information in the app became a transparency and control mechanism that allowed prosumers to observe how they perform with regards to the regulatory conditions. This was possible because the timing and the content of the behavioural intervention matched the information required for regulatory compliance. Nevertheless, the intervention was initially intended to serve as a nudge by providing intuitive guidance that leads consumers to adapt everyday choices (see Thaler & Sunstein, 2008). Instead, the information in the app became a monitoring tool for a different policy domain that was urgently on participants' minds, but had little connection to the nudges intended in the original field experiment. On the one hand, this indicates that feedback – both in nudging and other digital information tools – can have a positive co-benefit: transparency. Policy measures that are designed for the intuitive behavioural system can have positive linkages to the rational system. On the other hand, the lesson is that nudging interventions have limited efficacy for their original objective of intuitive guidance when the regulatory framework is dominant.

In our study, the timing of the intervention came at a critical point in the timeline: near the end of the year, when the "deadline" for reducing surplus was imminent. This unique circumstance allowed us to identify policy-related reactions out of the time series data because reactions would have to be swift under urgency. The information was timely, and the nudging set-up that surrounded this specific information likely contributed to awareness. The limitation is that we do not have variation in treatment: what if prosumers had received the regulatory information earlier in the year? Would the reaction be the same, or would there be a procrastination effect because urgency is low? Reminders are known to be effective for other policy domains with high financial stakes (e.g., Ericson, 2017), while the timing of behavioural interventions appears to be of minor importance in controlled experiments (e.g., Le Maux & Necker, 2023). Thus far, the timing of interventions has received little attention in the energy context; we would therefore welcome future research analysing the timing of the delivery of energy feedback in controlled experiments.

Policy design

The above takes a positive view by identifying opportunities for interplay between information feedback and regulation. However, in the case we study, the corresponding incentives were *not* aligned, which is critical for policy design. On an individual level, this creates a discrepancy between the decision-making systems. The observed reactions do not reflect enduring adjustments to everyday choices, but rather short-term adjustments to a regulatory notch. The notch dominated the nudge, and the available information in the metering feedback was used accordingly. On a broader policy level, there is a tension between the regulatory incentives and the information incentives. Information incentives are typically designed to represent broader energy policy objectives, i.e., saving energy and encouraging prosumerism (cf. European Environment Agency, 2022). Yet the regulatory frameworks set short-term incentives to adjust in the opposite direction.

That raises the question *why* the policy was set this way. While the Croatian policy makers offer no explicit explanations on this issue, the arguments on grid costs and equity concerns from the literature appear plausible also in the Croatian case. Yet ironically, two particular strategies cited in the literature for mitigating rebound, i.e., limiting monetary gains and providing information, backfired into actually encouraging rebound behaviour in our Croatian case. This has implications for the design of prosumer policy.

On the aggregate level in Croatia and even further at the EU level, prosumers collectively contribute to economy-wide green priorities. We can only look at individual cases with our small sample, but the results suggest that the policy setting is likely to have substantial aggregate effects. If our findings are representative of the Croatian population, the policy results in lost renewable energy potential and excess energy consumption. If our results are *not* representative, i.e., prosumers without the app do not manage to avoid the status switch, there would be high economic costs from sub-optimal choices and excess compliance burden. Our study does not quantify the full economic cost, but both scenarios imply a substantial welfare loss, particularly regarding the observed self-curtailment. Curtailment has been studied mainly from a technical perspective, where the question is how grid constraints can be managed effectively and efficiently. Our results point to a different, paradoxical type of curtailment: prosumers who voluntarily shut off their production to comply with a regulatory system that is meant to promote precisely this production.

In this context, it is also appropriate to consider that policy design has secondary effects on the supply side, in our case from the perspective of the local collective. The Croatian energy cooperative ZEZ, which was responsible for rolling out the case study, has a general interest in building up energy communities. Yet with the policy reaction, the smart meter data collected from existing customers are potentially biased downward in their capacity to produce and share renewable energy. The distortion created by the adjustment to the policy hence prevents local organizations from effectively using the collected data in calculating future business models, especially when the regulatory framework is subject to frequent revision and uncertainty as in the Croatian case. Yet these business models are important for enabling decentralized generation in the energy transition (e.g., Botelho et al., 2022; Brown et al., 2019).

Going forward, the Croatian prosumer policy does no longer feature the two-model system in the form we study here. The new framework removed this particular notch. However, the new policy framework still includes other notches. For example, the price for electricity drawn from the grid changes drastically at a 6-month-threshold of 3,000kWh from October 2023 (Parliament of Croatia, 2023). This is another example of a notch that metering feedback would make salient. Similar to the notch we study, it creates links with other policy domains – for instance to social policy, since older buildings have higher consumption.

Conclusion

Conclusions for policy

Actual policy frameworks have little choice but to set thresholds to distinguish consumer groups – yet our evidence emphasizes that the reactions to such thresholds can be drastic and run counter to overarching policy objectives. We therefore recommend for policy makers to pay attention to notches in the policy design and discuss the trade-offs between clear regulation and potential behavioural distortions with stakeholder groups across department boundaries.

In principle, both metering feedback and regulation could be used to support the overarching objective of energy policy for prosumers, namely increasing domestic PV generation and encouraging self-consumption to ultimately decrease consumption from the grid. Yet, the examined outcome did not match the overall target in the Croatian policy framework. We hence encourage policy makers to consider the potential of information policies to support regulatory frameworks and tax systems, since our results suggest that there is opportunity to leverage the intersection to create synergies. More generally, the same argument applies to the broader group of behavioural interventions, including nudging and labelling. Our results show that information can set off drastic behavioural change – the open question is how to best leverage this in policy portfolios. Better alignment would allow individual prosumers to better utilize the very different types of incentives that are ultimately intended to promote distributed energy resources and private households' participation in the energy transition. This, however, requires a collaboration across departments that differ not only in objectives, but also in the approach to policy design questions.

Our results provide insights on how tax systems, regulatory frameworks, and energy policy are intertwined. Information, like the metering feedback in our case, can help consumers adjust ex-post, but the preferable option would be an ex-ante alignment in policy design. Especially when new actors and business models emerge in a transition period, existing and emerging legislation should be reviewed for alignment to avoid undesirable consequences. This ideal recommendation pre-supposes that there is agreement on what is desirable. Provided there are legitimate concerns that require some form of restriction on prosumer benefits, the major policy implication is the need for alignment between policy areas, not only by creating additional provisions, but by jointly considering policy design across domains.

Conclusions for research

With the limitations inherent in the ad-hoc research opportunity, we can identify prototypical short-run reactions, but are unable to estimate the structural parameters or dig deeper into the individuals' decision-making process. These are open questions that we hope will receive further attention, so that an understanding of the mechanisms can deliver more specific principles for policy design. For future research, we see gaps both at the micro- and at the system-level. At the micro-level of individual households, more work is needed to understand how prosumer behavior is shaped by the interplay of information and regulation. This is not limited to unintended consequences. Future research will be needed to provide a better understanding of the channels and mechanisms through which feedback information might provide co-benefits to regulation. At the system-level, conceptual and simulation studies should incorporate and explore the details of policy design and especially notches. The big picture of broad design options, e.g., net metering versus net billing, has received more attention than the specific details of how they are applied. We show that these details matter and call for more work in this area.

Finally, the results are a call to behavioural scholars to share knowledge: economists know notches, psychologists know nudges, and engineers know technology. In the unique research opportunity presented in this paper, these three sciences came together to analyse and understand the policy effects. The output from this collaboration highlights the value of inter- and transdisciplinary work in energy research. Likewise, we believe the Croatian case can be informative across country boundaries, as European stakeholders jointly struggle to devise and evaluate the policy puzzle needed for the energy transition.

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Data Availability The data were collected as part of the Horizon 2020 project NUDGE and are not publicly available. Requests for academic use can be made to co-author Erica Svetec.

Declarations

Conflict of Interest For disclosure, the authors Erica Svetec and Lucija Nad were employees of ZEZ cooperative at the time of writing, and ZEZ as a company is affected by the Croatian regulatory framework. There are no further conflicts of interest for any of the authors in this paper.

Appendix

A. Details on Experiment Design and Sample Description

The following provides information on the experiment, the sample, and the content of the mobile app. This content is largely based on Deliverable 2.3 of the NUDGE Project. For further details, refer to NUDGE (2023), where the project files are continuously updated.[15]

[15] See the knowledge hub on the project website: https://www.nudgeproject.eu/knowledge-hub/

Fig. 7 Screenshot from mobile app showing the regulation-relevant content page

Table 4 Descriptive statistics for smart meter data from June 1, 2022 to Feb 28, 2023

	Mean	SD	Min	Max	N
Consumption	22365.48	18083.02	0.33	165013	9206
Production	10807.83	11106.09	0.00	75755.75	9206
Self-Consumption	5724.23	7129.75	0.00	72834.25	9206
Grid Out	5083.6	7242.12	0.00	59187	9206
Grid In	16641.26	15967.43	0.00	138464	9206

Figure 7 shows screenshots from the mobile application for the aggregated production and consumption of the households. This is the information provision that makes regulatory status transparent.

Table 4 contains further information on the sample. This provides descriptive statistics for all participants in the sample. Consumption and production are the outcomes plotted in the main analysis. Grid out is energy taken from the grid, while grid in is energy returned to the grid. The reported figures

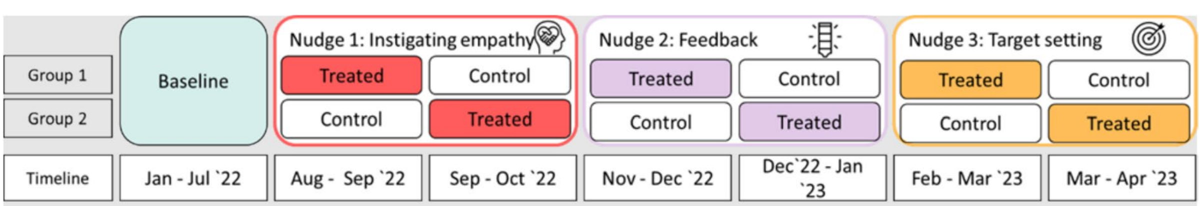

Fig. 8 Timeline of all three interventions in the Croatian pilot of the NUDGE project

are mean, standard deviation (SD), minimum (min), maximum (max), and the total number of observations (N). Information on the energy-related variables is reported for the same timeframe as the case study plots in the main analysis.

The data collection underlying the natural experiment was part of the larger Horizon 2020 project NUDGE. Overall, there were three interventions delivered through the mobile app. The information relevant for the regulation was part of the second intervention period. For an overview, Fig. 8 shows the overall timeline of the project. The figure first appeared in Deliverable 2.3 of the project (copyright confirmed). The nudging interventions were usually delivered to two sub-groups at different times in a treatment–control approach. The policy-relevant information is however available to both groups over the entire second intervention period, irrespective of the group assignment.

B. Results for Additional Participants

The case studies in the main paper are selected by the authors. For transparency, the following contains the time series plots for all participants. The participants are grouped into the best fit according to the five prototypical reactions (Figs. 9, 10, 11, 12 and 13). Participants already included in the main case studies are repeated for the convenience of the reader.

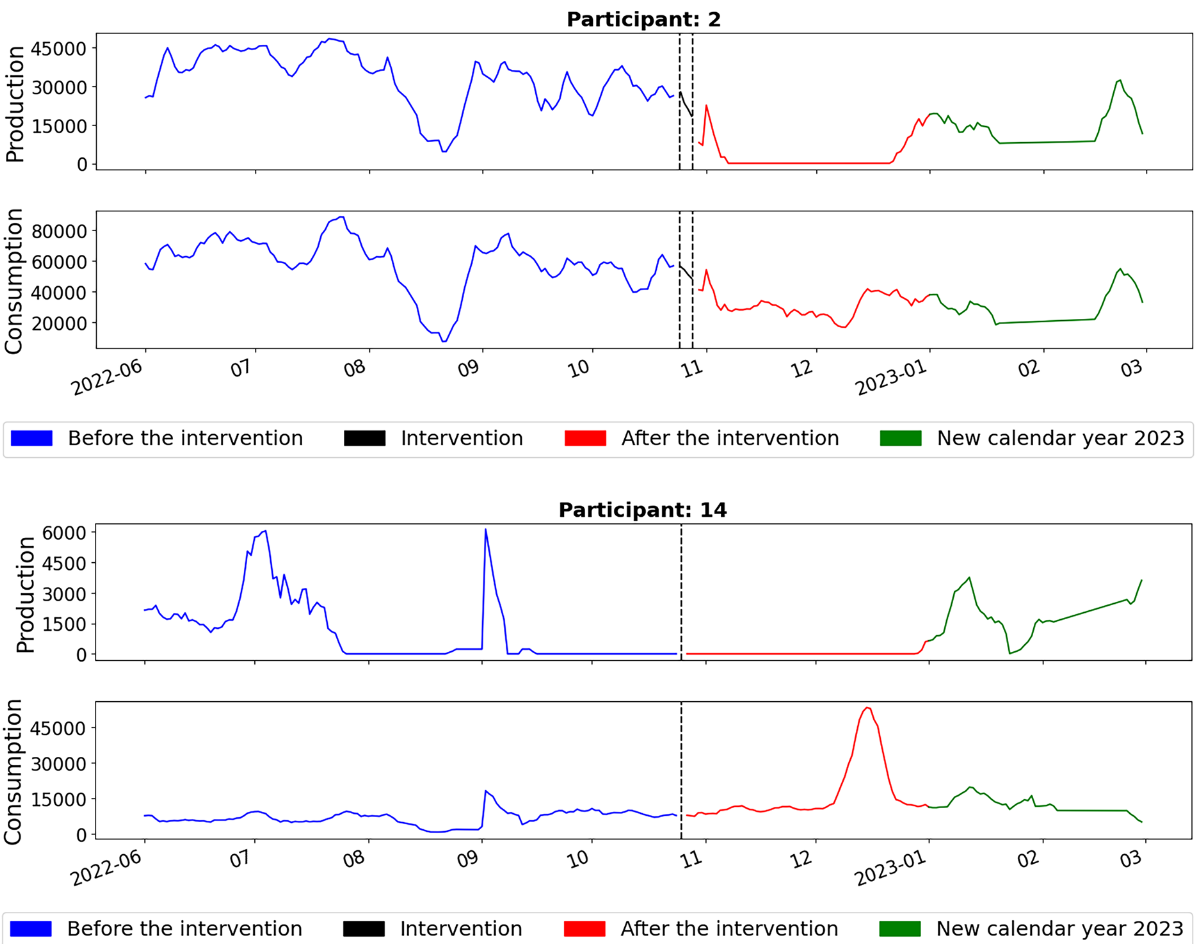

Fig. 9 Temporary shutdown of the PV plant until year-end

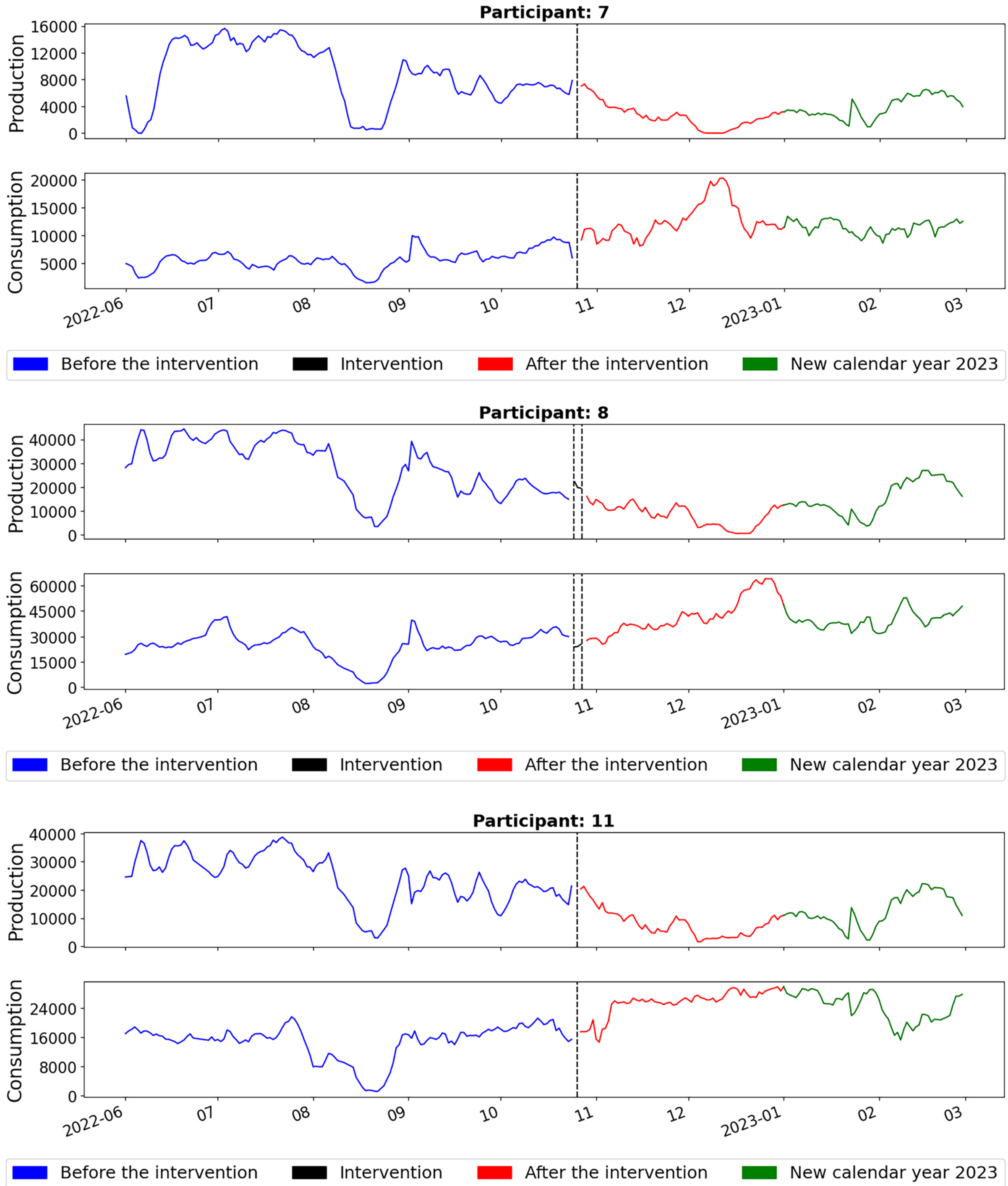

Fig. 10 Increase consumption until year-end

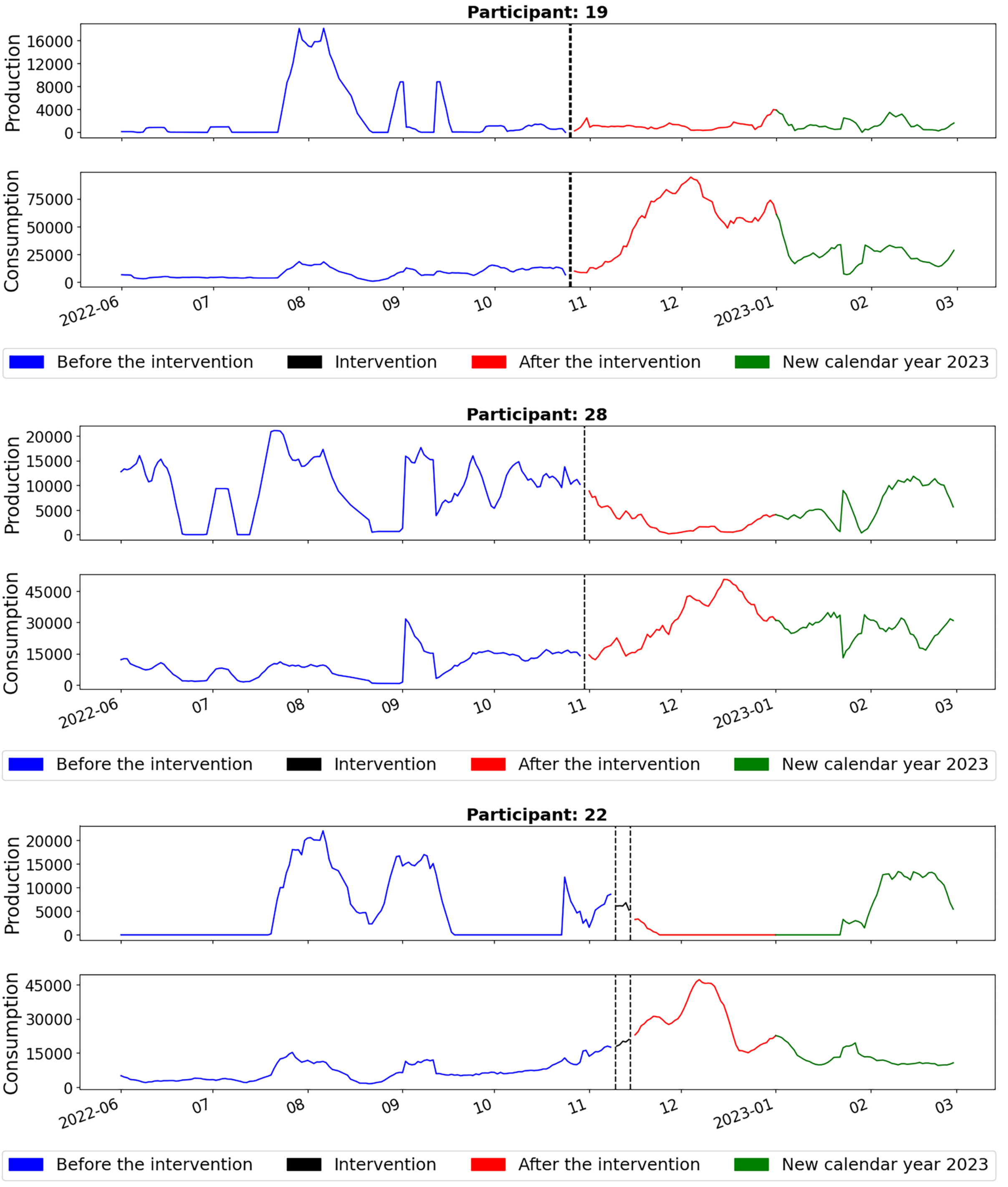

Fig. 10 (continued)

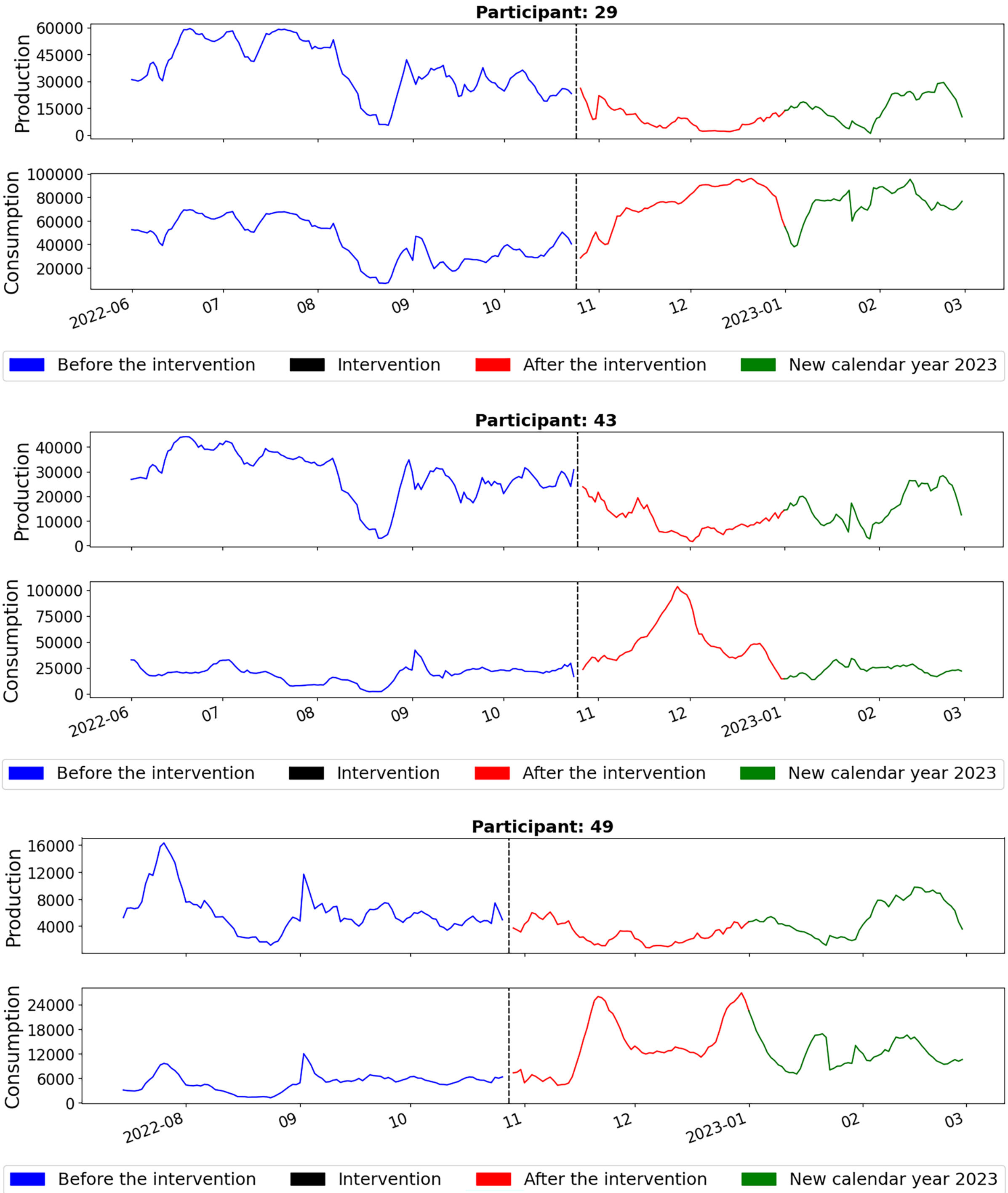

Fig. 10 (continued)

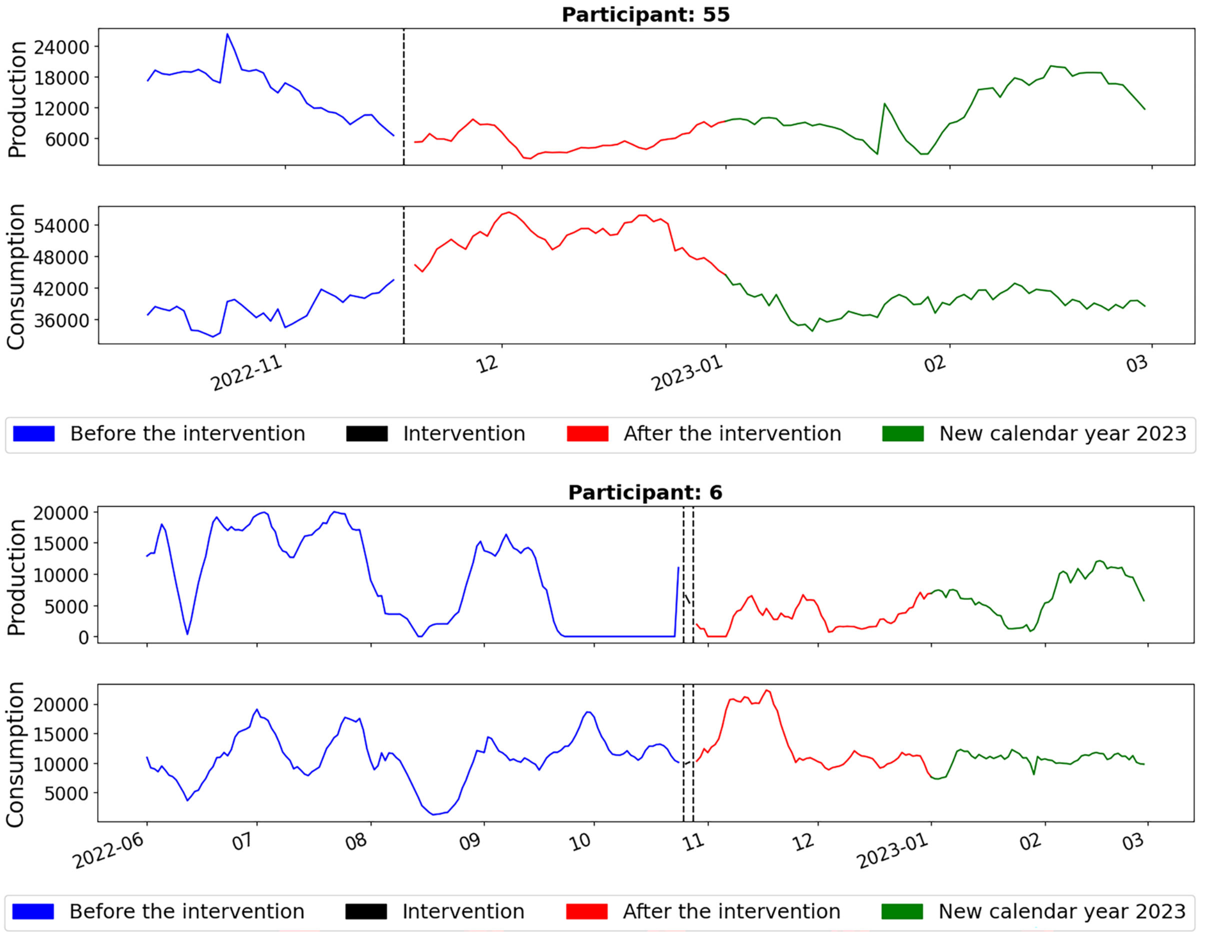

Fig. 10 (continued)

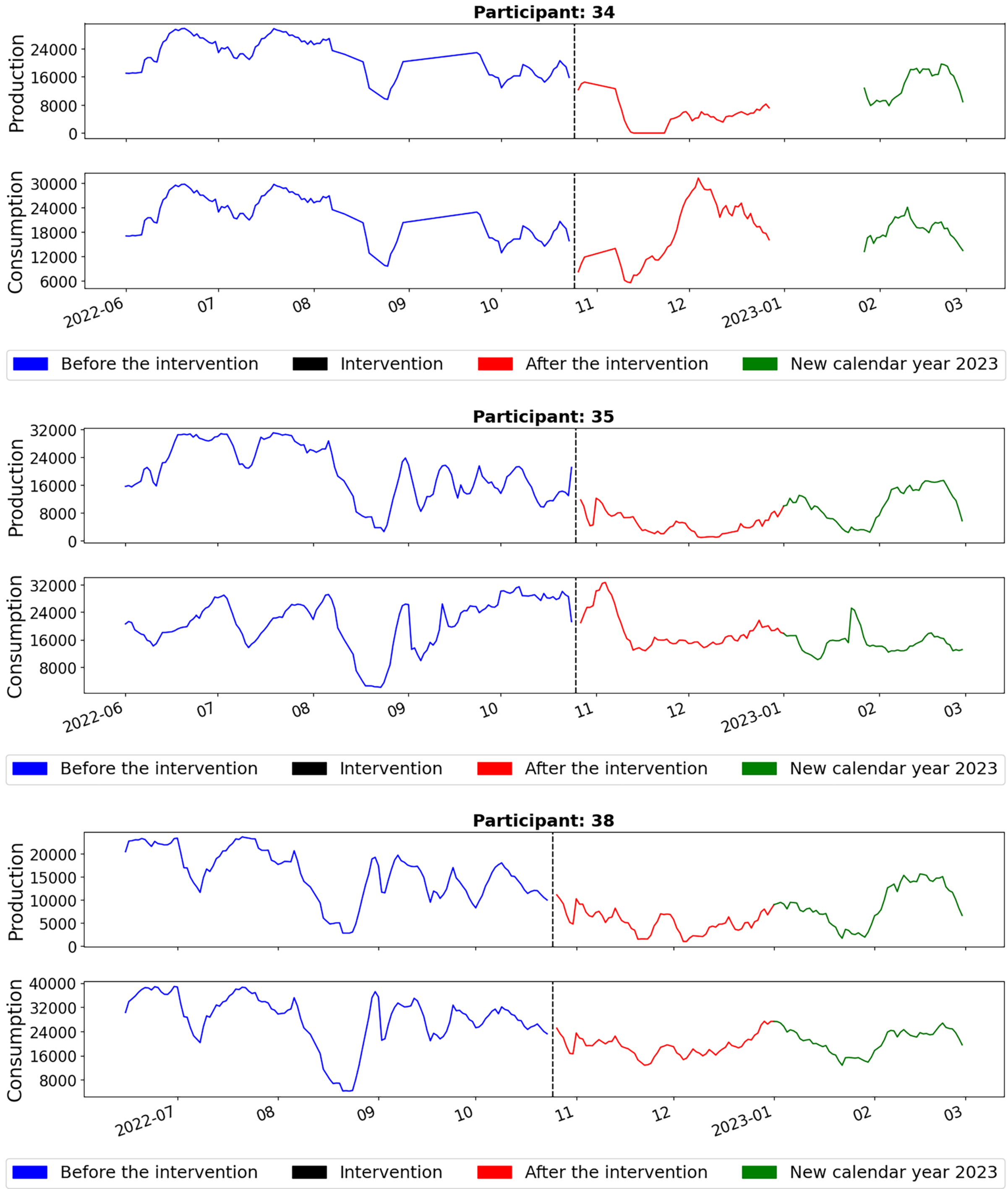

Fig. 11 Decrease consumption and maintain beyond year-end

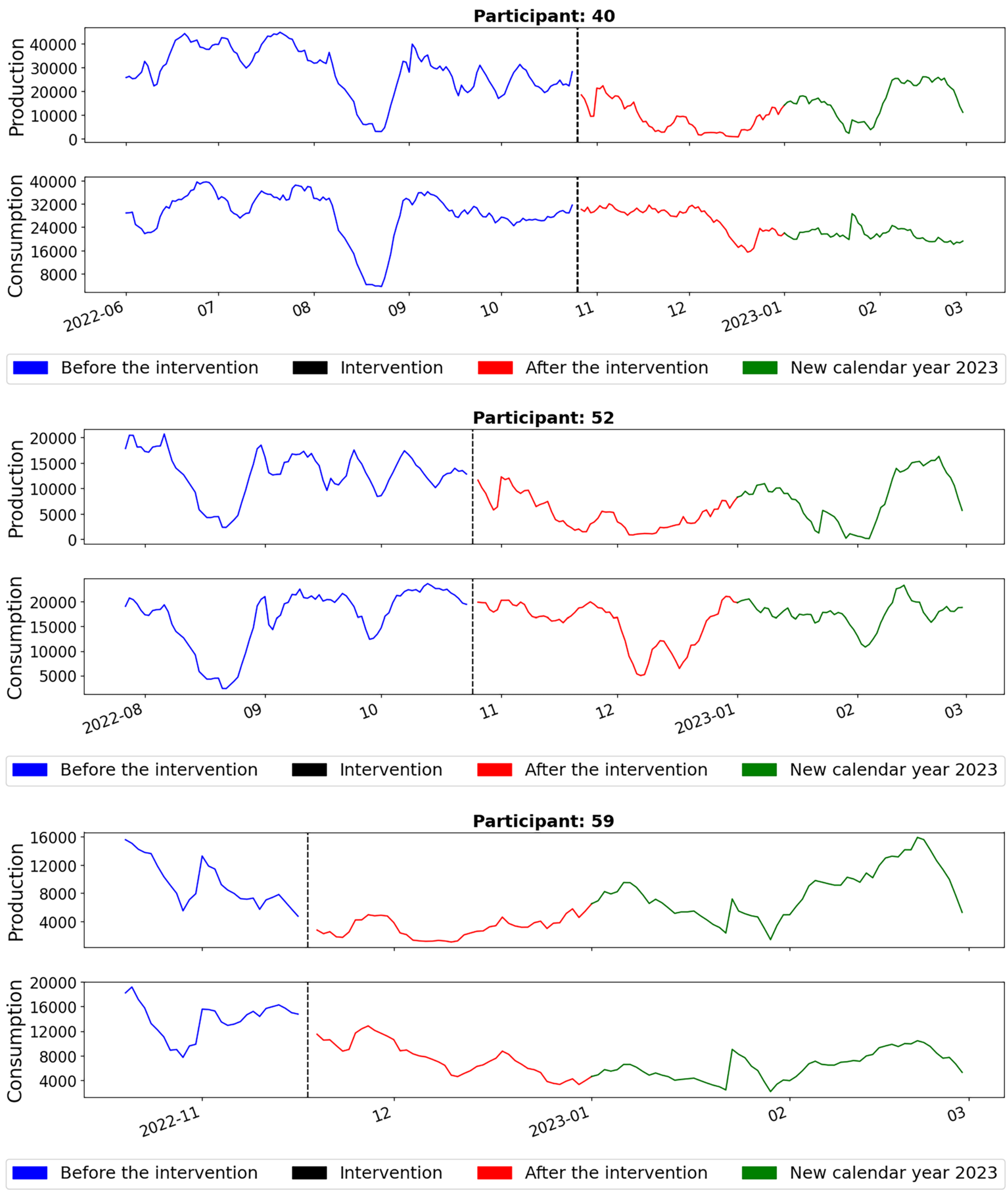

Fig. 11 (continued)

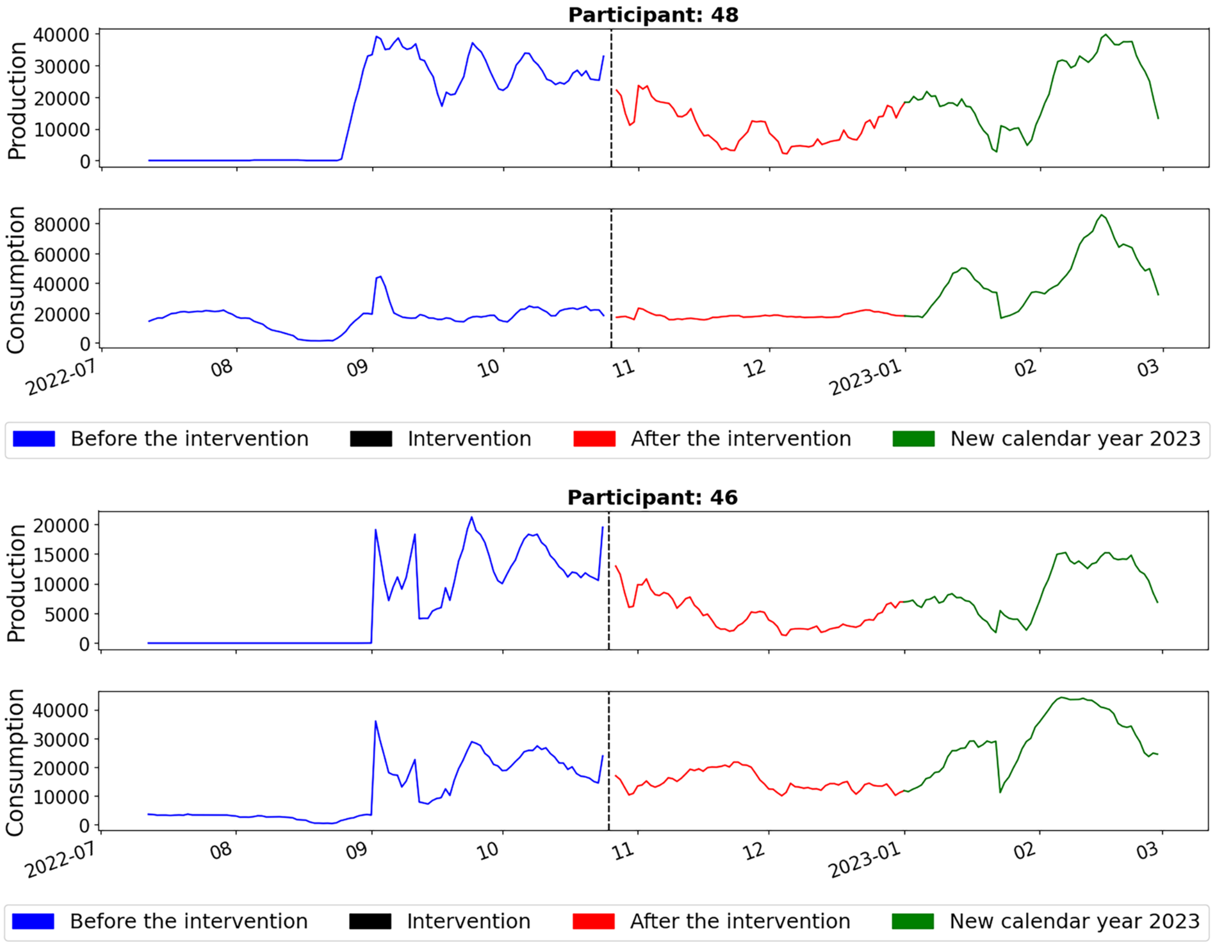

Fig. 12 Decrease consumption but bounce back with the new year

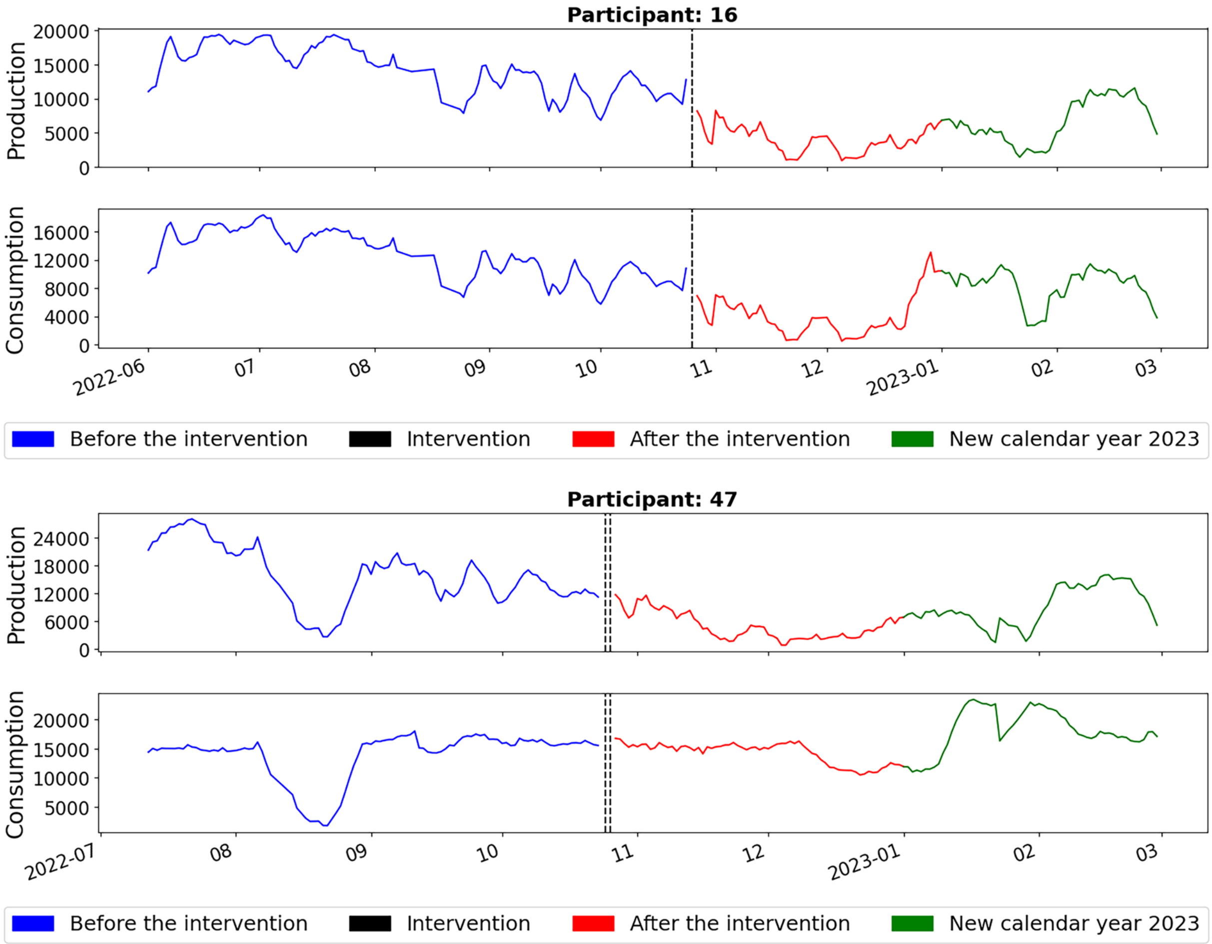

Fig. 12 (continued)

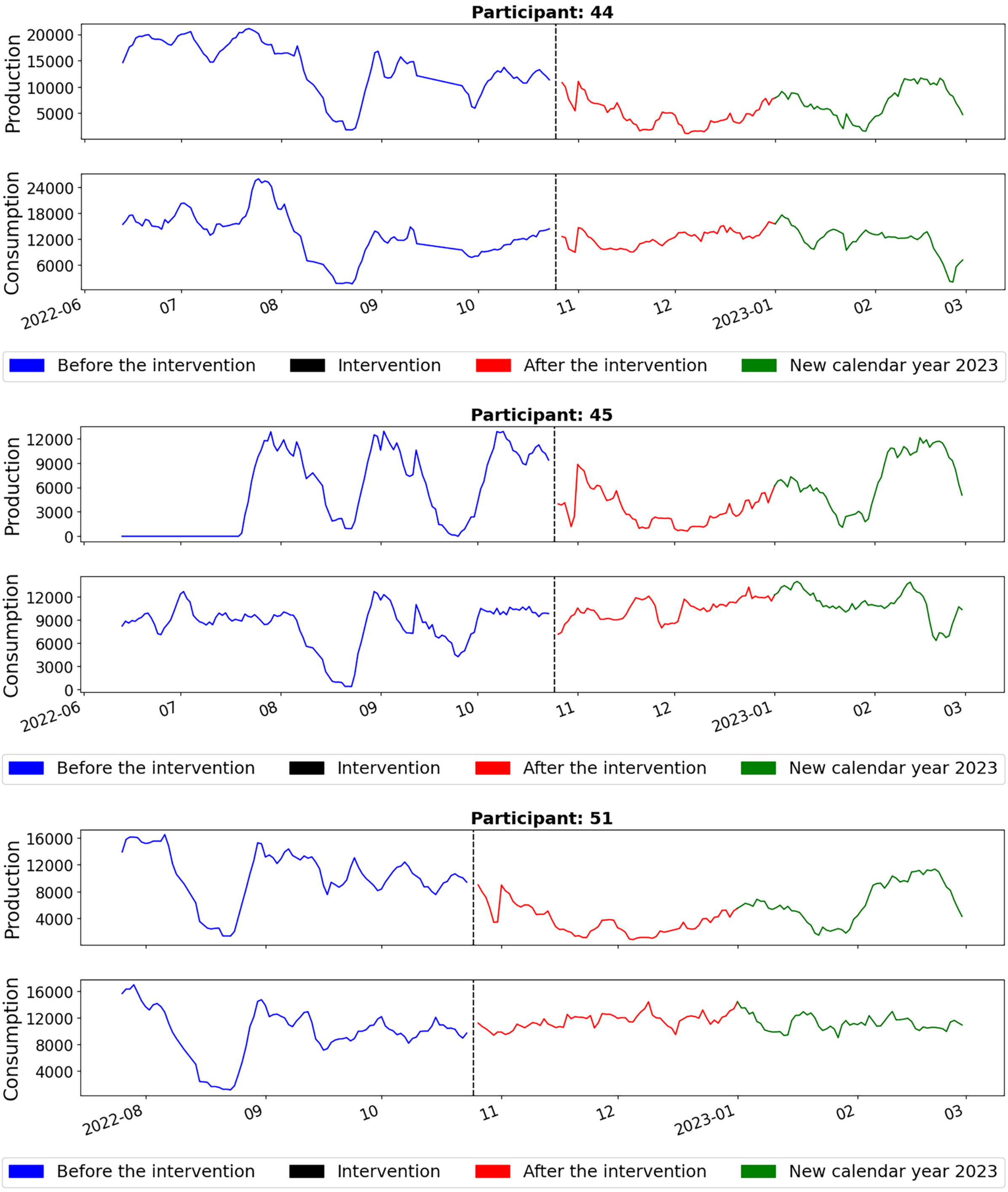

Fig. 13 No visible reaction during the intervention period

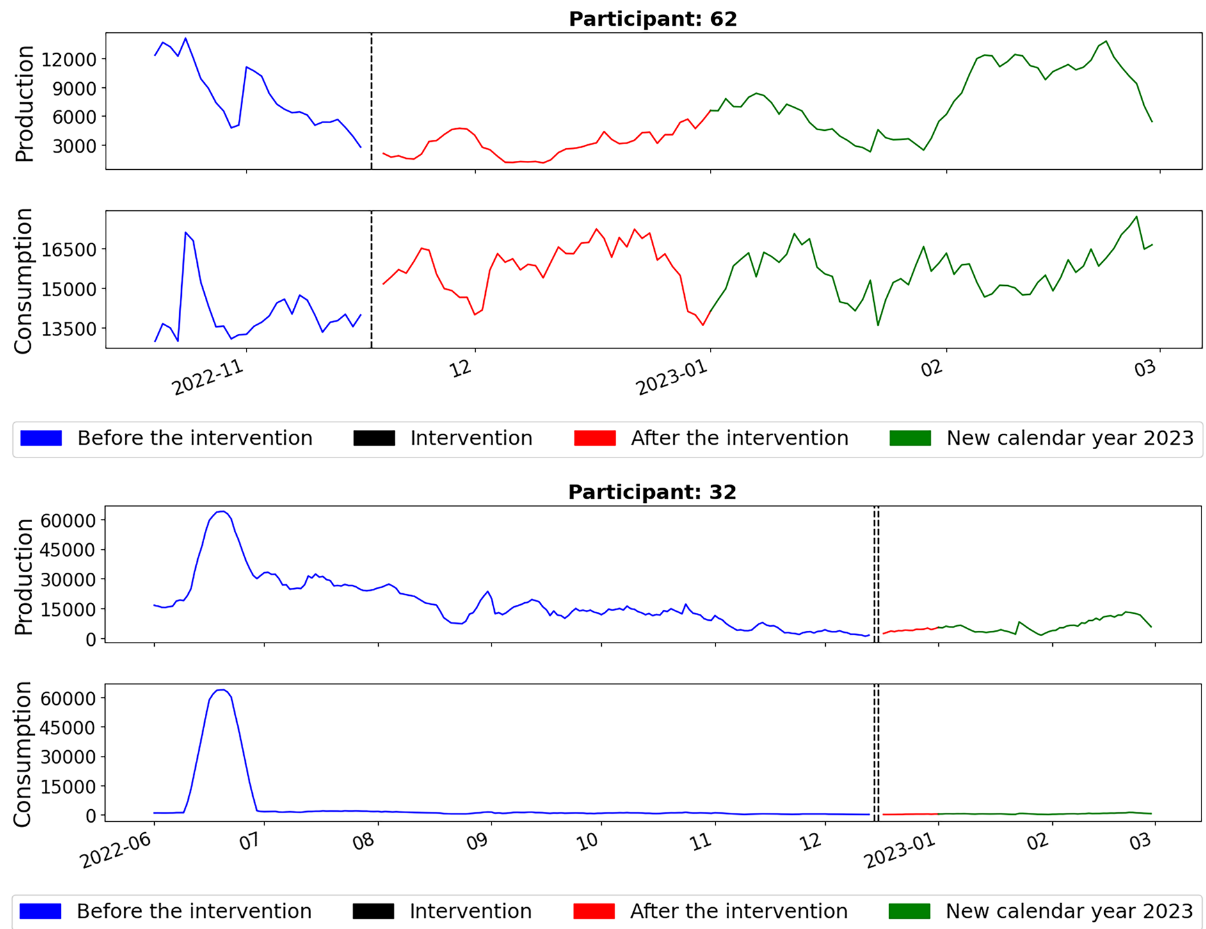

Fig. 13 (continued)

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