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Security of supply and the energy transition: The households' perspective investigated through a discrete choice model with latent classes

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ABSTRACT

A consumer-centric, market-based approach to the security of electricity supply has been recognized as increasingly important in the context of the energy transition. Nonetheless, there is no clear-cut evidence regarding the drivers of consumer preferences toward security and the perceived trade-offs between security and sustainability. Using stated preference data, we develop a discrete choice model with latent classes to assess the willingness-to-accept (WTA) of Swiss households for variations in the frequency and duration of blackouts, while accounting for the primary energy sources used for generation. Our WTA estimates range from slightly negative values up to ten times the current electricity prices, depending on the characteristics of both blackouts, and respondents. More specifically, we identify three latent classes showing different preferences toward blackout frequency and length, but also different sensitivities toward blackouts associated to nuclear or solar generation, as well as toward prospective changes in the generation mix. Energy illiteracy, concern about the economic impact of blackouts, and concern about nuclear generation are the main determinants of class membership probability.

1. Introduction

The security of electricity supply (SOES), i.e. the ability of an electricity system to guarantee the supply of electricity to customers with a clearly established level of performance,[1] is a key determinant of economic growth and consumer welfare in modern economies. In the past decade, however, the energy transition started in several countries has created new threats to the SOES, among which the need to decommission carbon-intensive generation plants, counterbalance the volatility of intermittent renewables, integrate the contribution of distributed generation, and finally upgrade transmission and distribution grids pursuant to the new structure of the electricity system (Larsen et al., 2017).

Throughout the 2010s energy companies, policy makers, energy regulators, and academics have discussed and tested new tools to ensure the desired level of SOES during the transition toward an increasingly decentralized and low-carbon energy system. The initial steps to ensure security have mainly been based on a supply-side approach: several European countries have indeed introduced capacity remuneration schemes to support unprofitable programmable generation plants still needed for security (Olmos and Pérez-Arriaga, 2013; ACER/CEER, 2017). In the second half of the decade, however, the European Commission has started to express concern about the distortions possibly induced by these mechanisms (European Commission, 2015b; European Commission, 2016). The role of consumers in determining the desirable security level - and possibly even contributing to security itself - has gradually come into focus. The Commission has thus suggested that the wholesale market should be allowed to express scarcity signals through higher electricity prices along the different maturities: these prices should reflect both the adequacy level provided by the system, and the value of security to consumers (European Commission, 2015a). The Clean Energy Package approved between 2018 and 2019 has further emphasized the need of a market-based, consumer-centric approach to SOES in order to replace uncoordinated and potentially distortive capacity mechanisms introduced on a national basis. Regulation (EU) 2019/943, among other things, provides for the removal of caps and floors on the prices in the wholesale markets for electricity, and states that the maximum and minimum clearing prices adopted for technical reasons should be determined taking into account the value of lost load (VOLL), defined as “the maximum electricity price that customers are willing to pay to avoid an outage”.

A consumer-centric approach to the SOES has become increasingly popular also among electricity retailers. Thanks to the recent technological progress, these companies are often able to provide customized supply contracts which, among other features, may include higher security levels for selected customers, or ensure lower purchase costs for the consumers who are ready to participate in demand response programmes. The SOES, traditionally regarded as a public good

Abbreviations: DC, discrete choice; VOLL, value of lost load; WTA, willingness to accept; WTP, willingness to pay; SOES, security of electricity supply.
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[1] Art. 2, Regulation (EU) 2019/941.

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(Abbott, 2001; Finon and Pignon, 2008), is gradually taking on some private good features, and markets for flexibility or higher security start to emerge.

Within this setting, a careful assessment of the value of SOES for the different categories of consumers is increasingly important from both a regulatory, and a marketing perspective. In the past few decades several researchers have undertaken this task using different methods, ranging from the production function approach to case studies, and from the analysis of stated preferences to the use of proxies or revealed preferences. However, even when focussing on the residential sector and considering relatively recent analyses of countries with comparable economic conditions and security levels, the estimates of the value of security span over a very wide interval. The evidence regarding the drivers of this variability is relatively limited and not always coherent across different studies. Moreover, even if the energy transition has brought in the foreground the link between electricity security on the one hand, and the replacement of carbon-intensive generation with low-carbon generation facilities on the other hand, very few studies consider consumer preferences toward both the SOES, and the different primary energy sources or electricity generation technologies.

Our analysis focusses on the case of Switzerland, a country with a very high level of security[2] but committed to phasing out nuclear generation, contributing to approximately 40% of inland productions, and replacing it with new low-carbon generation plants.[3] The shift from nuclear to other low-carbon generation technologies, expected for the medium term, obviously entails a challenge to the SOES, that is further complicated by the developments observed in the energy markets, regulation, and infrastructures of the neighbouring European Union countries (Hettich et al., 2020). Since 2011, when the decision of phasing out nuclear generation was made, the Federal Government and Parliament have drafted and launched a long-term energy strategy which outlines an overarching restructuring of the Swiss energy system and regulation, in order to address security next to the sustainability and affordability of the electricity supply.[4] The energy transition is gathering speed and the acceptance among citizens is increasing, as witnessed by the positive outcome of the referendum on the energy strategy held in 2017. Future decisions on the identification and sizing of new infrastructures will however benefit from a measurement of the value that consumers place on security, an assessment of consumers' views on the trade-offs between security, sustainability, and affordability of electricity supply, and finally an investigation into the demographic or behavioural traits that may exert any systematic influence on consumer preferences.

Our contribution to the debate concerning the optimal level of SOES and the design of an energy system matching the expectations of electricity consumers is twofold. On the one hand, we explore the preferences of Swiss residential consumers toward both the risk of supply outages, and a set of primary energy sources used for generation.[5] On the other hand, we investigate the demographic and behavioural drivers of heterogeneity in household preferences toward security. Our analysis is based on stated preference data collected by means of a survey distributed in 2015. More specifically, we use a discrete choice (DC) experiment to measure the households' willingness to accept (WTA) for an increase in the frequency of long and short blackouts, and include the primary energy sources used for generation as one of the attributes of the available alternatives. The specification we choose is a hybrid DC model with latent classes: this model allows us to provide a nuanced explanation of the drivers that determine heterogeneity in consumer behaviour, and include the attitudinal motives that are not directly observable from the data. Our evaluation of the value of SOES to household consumers may support the definition of specific details of the wholesale electricity market design, and provide a basis for deciding about the desirable security level. Our assessment of the trade-offs that consumers perceive between the SOES and the use of specific generation technologies may instead support decisions concerning specific investments into new generation facilities, and facilitate the design of customized electricity supply contracts.

Our contribution develops as follows. Chapter 2 collects the relevant suggestions from the economic literature. Chapter 3 and 4 describe our econometric method, survey, and data. Chapter 5 presents our results, and finally chapter 6 discusses the novelty of our findings and analytical approach, together with the resulting policy implications.

2. Literature review

Household preferences with respect to the SOES have been investigated by several researchers and with growing interest over the last few decades. While the SOES is, generally speaking, a multifaceted concept stretching to different time horizons and involving several actors along the electricity supply chain (Rodilla and Batlle, 2012), the analyses considering the consumers' perspective focus on its practical, short-term impact, i.e. an electricity outage or blackout[6] and its material and immaterial damage. More specifically, these studies measure the damage associated to each unit of unsupplied electricity, or the damage caused by a blackout with given characteristics, or finally a household's willingness to pay (WTP) to avoid a blackout or WTA to accept it (Table 1).

2.1. Aims of the existing analyses

Most of the studies on household preferences with respect to the SOES have been developed in order to support decisions regarding the optimal investment into system adequacy. By assessing the marginal value of security to households – and usually also to manufactories and service companies – these analyses provide a reference against which the marginal cost of preserving or improving the current level of SOES can be evaluated. The value of SOES to residential consumers has also been investigated in order to inform the design of incentive regulation schemes set up to encourage distribution system operators to reach a given quality standard (Bertazzi et al., 2005; Carlsson and Martinsson, 2008; Kjølle et al., 2008; Baarsma and Hop, 2009; Bliem, 2009). Other studies have instead contributed to the definition of specific details of the electricity market design, such as the price caps applied in the commodity markets (CEPA, 2018), the functioning of the rationing schemes in case of emergencies (de Nooij et al., 2009; Kim et al., 2015), or the structure of capacity and balancing markets (London Economics, 2013; Shivakumar et al., 2017). Finally, a relatively recent stream of literature has assessed the heterogeneity of consumer preferences toward the SOES and explored its drivers, with the aim of supporting the design of customized electricity supply contracts matching the expectations of consumers as regards the continuity and other qualitative features of the electricity supply (Abdullah and Mariel, 2010; Pepermans, 2011; Amador et al., 2013).

2.2. Methods used

Most of the analyses concerning the value of SOES for residential consumers rely either on the production function method, or on the analysis of stated preferences (Table 1). A few studies have analysed

[2] Switzerland ranks among the European countries with the lowest average duration of unplanned outages per year, according to Elcom (national regulatory authority in Switzerland), 2020: "Qualità dell'approvvigionamento elettrico 2019 - Rapporto della ElCom".

[3] Swiss Federal Office for Energy, 2018, "Chronologie der Energiestrategie 2050"; Swiss Federal Office for Energy, 2019, "Energiestrategie 2050 Monitoring-Bericht 2019, Kurzfassung".

[4] Swiss Federal Office for Energy, 2018, "Chronologie der Energiestrategie 2050".

[5] The residential segment accounts for approximately one third of the final electricity consumption in Switzerland (Bundesamt für Energie (BFE), 2020).

[6] The two terms are used here as synonyms.

Table 1
Value of SOES for residential consumers in comparable countries since year 2000.

Reference	Method[a]	Region	Year	Value of security for residential consumers (in 2015 USD)[b]
Bertazzi et al., 2005	CV	Italy	2003	WTP: 4.2, WTA: 19.4; VOLL: 28.81
Carlsson and Martinsson, 2007	CV	Sweden	2004	WTP: announced blackout: 1.07; unannounced blackout: 1.62
Baarsma and Hop, 2009	CV	Netherlands	2003–2004	WTA: 5
Carlsson et al., 2011	CV	Sweden	2004; 2005	WTP for announced blackouts lasting 1 h: before storm Gudrun 1.08, after storm with no cheap talk script: 0.49, after storm with cheap talk script: 1.68; WTP for unannounced blackouts lasting 1 h: before storm 1.61, after storm with no cheap talk script: 0.79, after storm with cheap talk script: 2.34
Ozbafli and Jenkins, 2015	CV	North Cyprus	2008	WTP: 28.39 USD/month for having zero blackouts
Woo et al., 2014	CV	Hong-Kong	2013	Outage cost: 45.67
Kim et al., 2015	CV	South Korea	2014	WTP: unannounced 2 h blackout: 2.8; announced 2 h blackout: 2.2
Kjølle et al., 2008	CV, direct worth	Norway	2009	WTP: 0.93; direct worth: 2.16
London Economics, 2013	CV, DCE	United Kingdom	2013	VOLL based on WTA: 11.04–18.76 USD/kWh; VOLL based on WTP: 0–4.39 USD/kWh
CEPA, 2018	CV, PF	EU-28 (Malta not covered in the survey)	2018	VOLL: unannounced blackout: 1.66–25.45; blackout with 24-h advance notice: 0.92–14.12
Carlsson and Martinsson, 2008	DCE	Sweden	2004	WTP for a 4 h blackout: weekday, winter: 1.27; weekday, summer: 1.84; weekend, winter: 5.06; weekend, summer: 3.44;
Pepermans, 2011	DCE	Belgium	2004–2005	WTA: 45.7–76.3
Bliem, 2009	DCE	Austria	2007	WTA: 3 min blackout: 1.49% of the electricity bill; 4 h blackout: 16.05% of the electricity bill
Ozbafli and Jenkins, 2016	DCE	North Cyprus	2008	Compensating variation: 6.27 USD/month for having zero blackouts in summer, 24.33 USD/month for having zero blackouts in winter
Amador et al., 2013	DCE	Canary Islands	2010	WTP: 2.85 USD/month for having one unannounced blackout less per year; 1.43 USD/month for reducing blackout duration by 5 min
Reichl et al., 2013	DCE	Austria	2011	WTP: 2.07
Cohen et al., 2016	DCE	RO, BG, GR, HU, PL, FI, ES, EE, FR, SE, DK, IE, NL, DE	2012–2013	WTP: 0.49–5.36
Longo et al., 2018	DCE	Estonia, Netherlands, Portugal	2018	VOLL - Planned outages: based on WTP: EE 0.38, NL 0.68, PT 0.65; based on WTA: EE 21.32, NL 27.81, PT 29.00. VOLL - Unplanned outages: based on WTP: EE 0.73, NL 1.15, PT 1.08; based on WTA: EE 19.94, NL 27.29, PT 18.8.
Merk et al., 2019	DCE (vignette study)	Germany, UK, Ireland	2013	Germany: WTP for electricity supply is 0.08 USDcent/kWh lower for any additional minute of blackout during one year; UK: WTP is 0.04 USDcent/kWh lower for any additional minute of blackout during one year
Abrate et al., 2016	DCE	Italy	2015	VOLL: 28.14
Morrissey et al., 2018	DCE	England	2015	WTP: 0.61; separate estimates for blackout timing
de Nooij et al., 2007	PF	Netherlands	2001	VOLL: 24.53
de Nooij et al., 2009	PF	Netherlands	2001	VOLL: 22.87
Leahy and Tol, 2011	PF	Ireland	2007	VOLL: 0–134.5 in Northern Ireland, 1.31–55.7 in the Republic of Ireland
Bliem, 2005	PF	Austria	2007	VOLL: 20
Linares and Rey, 2013	PF	Spain	2008	VOLL: 9.2–13.2
Zachariadis and Poullikkas, 2012	PF	Cyprus	2009	VOLL: 14
Castro et al., 2016	PF	Portugal	2010	VOLL: 10.62
Praktiknjo et al., 2011	PF	Germany	2011	VOLL: 23.19
Castro et al., 2016	PF	Portugal	2010	VOLL: 10.62
Shivakumar et al., 2017	PF	EU	2013	VOLL: 11.72

[a] CV: Contingent Valuation; PF: Production Function; DCE: Discrete Choice Experiment.
[b] Unless otherwise specified: direct cost, WTP and WTA are measured in 2015 USD per 1 h blackout, VOLL is measured in 2015 USD/kWh.

revealed preferences, evaluating the costs and characteristics of the back-up devices purchased by consumers, or investigated specific case studies, collecting quantitative or qualitative evidence as regards consumers' reactions when a blackout happens.

The production function method equates the value of security to that of the goods produced using electricity: every kWh not served is worth as much as the goods that electricity consumers would have produced through it. In the case of households, this approach assumes that they use electricity to produce leisure, and the worth of each hour of leisure is equal to the net hourly wage, or half of it for persons who are unemployed or not in the workforce (Munasinghe, 1980). The production function approach is thus based on easily accessible macroeconomic data: average or median hourly wage, rate of employment, use-of-time statistics, yearly electricity consumption of the average household, and finally, if relevant and known to the researcher, the hourly consumption profile and the rate of dependence on electricity for leisure production. The production function approach is relatively straightforward to implement and produces estimates which are usually easily comparable across countries, but is a relatively simplistic representation of how the residential segment is impacted by blackouts. First, the estimated blackout damage is deterministically computed based on the above mentioned variables, among which hourly wage and electricity consumption of households play a major role. Secondly, several analyses assume that the value of leisure is constant in time, space, and across the population, and neglect the hassle or material damage that households may suffer on top of the loss of leisure. Moreover, several researchers neglect the impact of advance blackout notice, as well as blackout duration and timing. Finally, the production function approach assumes that consumer preferences as regards security are symmetric, i.e. that the benefit gained from a unit improvement in SOES is equal in magnitude to the damage caused from a unit deterioration. This assumption, besides neglecting the suggestions of prospect theory (Kahneman and Tversky, 1979), is controverted by several empirical findings, as discussed in Woo et al., 2014, Abrate et al., 2016, Longo et al., 2018, Amoah et al., 2019, and more generally in Brown and Gregory, 1999.

The analyses based on stated preferences, usually exploiting contingent valuation or DC experiment data collected by means of surveys, help overcome some of the limitations of the production function approach. The use of survey data has, indeed, several advantages. First, surveys allow the researcher to investigate household preferences toward different blackout scenarios: duration, frequency, timing, and any other feature of the blackout that may matter to the analysis can vary in the survey questions. Secondly, they can be used to collect information on the respondent's demographic, behavioural, and attitudinal characteristics. The researcher can thus evaluate the relationship between the respondent's individual characteristics and his/her preferences toward the SOES. Finally, surveys allow the researcher to go beyond the measurement of the simple value of leisure lost. Indeed, the responses provided in contingent valuation studies or DC experiments implicitly account not only for the forgone leisure, but also for any material or immaterial damage perceived by the respondent, as well as for the actual substitutability of electricity as an input for the household's activities and leisure production. There are, however, also some important drawbacks in the use of survey data. As with any analysis relying on stated preferences, indeed, hypothetical bias and strategic behaviour often threaten the external validity of the results (Foster and Burrows, 2017; McFadden, 2017). Some researchers further argue that the respondents have very limited experience in answering questions concerning the value of SOES, and rather tend to feel entitled to a reliable and uninterrupted electricity supply. Moreover, the results obtained through different contingent valuation analyses or DC experiments are not always easy to compare, due to the diversity of the blackout scenarios under scrutiny and the variety of parameters that affect consumer preferences. Finally, the data collection process usually requires more time and resources as compared to the production function approach.

It is interesting to note that in recent years a few policy-driven analyses have tried to integrate the production function and stated preferences approaches, with the aim of producing easily comparable estimates, while accounting for different blackout scenarios (duration, timing, advance notification, …) and the dimensions of the blackout damage that are only known to the consumers (substitutability of electricity as an input, material and immaterial damage caused by a blackout, …). CEPA, 2018, for example, reports a computation of the VOLL for all EU Member States based on macroeconomic data, but complemented with survey data concerning the substitutability of electricity as an input for leisure production, the impact of advance blackout notice, and finally the impact of blackout duration. The ENTSO-E Proposal (ENTSO-E, 2020) for a common methodology for computing the VOLL pursuant to the requirements of Regulation (EU) 2019/943, in consultation at the time of writing, recommends as well that the VOLL should be computed based on a triangulation of methods. More in detail, the VOLL for the residential segment should be computed based on survey data, comparing the results obtained from contingent valuation and direct worth questions, whereas the VOLL for the industrial segment should be computed cross-checking survey data with the production function method.

2.3. Estimates and drivers of the value of SOES

A closer look at the existing estimates of the value of SOES provides interesting suggestions as concerns its magnitude, the strengths and weaknesses of the various methods, and finally the directions for further research.

Table 1 collects the estimates of the value of SOES for residential consumers provided by 31 analyses carried out since 2000 in countries showing comparable economic conditions and security of supply levels. For the sake of comparability, the estimates of each individual study have been converted into 2015 USD; when multiple blackout scenarios were evaluated within the same study, we selected the results concerning the scenario closer to the reference of a one hour long blackout without advance notice.

The estimated values of SOES show, indeed, a large variability. Stated preferences studies usually consider a variety of scenarios and produce results expressed in different measures. The main regularity for this kind of studies is the fact that, in line with the literature concerning the WTP/WTA discrepancy (Brown and Gregory, 1999), WTA values are two to four times higher than WTP values for the same country and scenario. The analyses based on the production function approach are instead easy to compare, and tend to yield, by construction, SOES values that are positively correlated to the average wages, and negatively correlated to the average electricity consumption in the residential segment.

The surveyed literature suggests the value of SOES to household consumers may depend on several drivers. Fig. 1 provides an overview of the characteristics of blackouts (left half of the histogram) and individual households (right half) that are mentioned in at least one of the analyses under scrutiny. Beyond the studies explicitly mentioned in Table 1, Fig. 1 includes other analyses developed before year 2000 and in countries whose economies and energy systems are very different from the Swiss ones (Munasinghe, 1980; Abdullah and Mariel, 2010; Woo et al., 2014; Kim et al., 2015; Nkosi and Dikgang, 2018; Amoah et al., 2019; Siyaranamual et al., 2020).

Higher blackout duration and higher blackout frequency, where considered, are generally associated to a higher WTP or WTA; most studies report however that the marginal increase in WTP or WTA values from an additional minute of blackout is positive, but decreasing with blackout duration. Unannounced blackouts generally harm more than planned ones. When blackout timing is considered, researchers usually find that the VOLL, WTP, or WTA values are lower during the night; there is instead no univocal evidence as regards the difference between working days and weekends, nor between Winter and Summer, although in colder countries Winter blackouts tend to harm more than Summer ones (Carlsson and Martinsson, 2008; Pepermans, 2011; Reichl et al., 2013; Abrate et al., 2016; CEPA, 2018; Morrissey et al., 2018; Nkosi and Dikgang, 2018; Amoah et al., 2019). The evidence concerning the role of demographic variables is not clear-cut across the studies included in the analysis: only higher income and longer education, where considered, are usually associated to higher VOLL, WTP, or WTA values.

The conflicting evidence as regards the role of some demographic variables, together with the scattered estimates of the value of SOES even for similar countries and consumption segments, suggest that a sizeable share of heterogeneity in consumer behaviour is still unexplained. Indeed, several researchers using random parameters for the

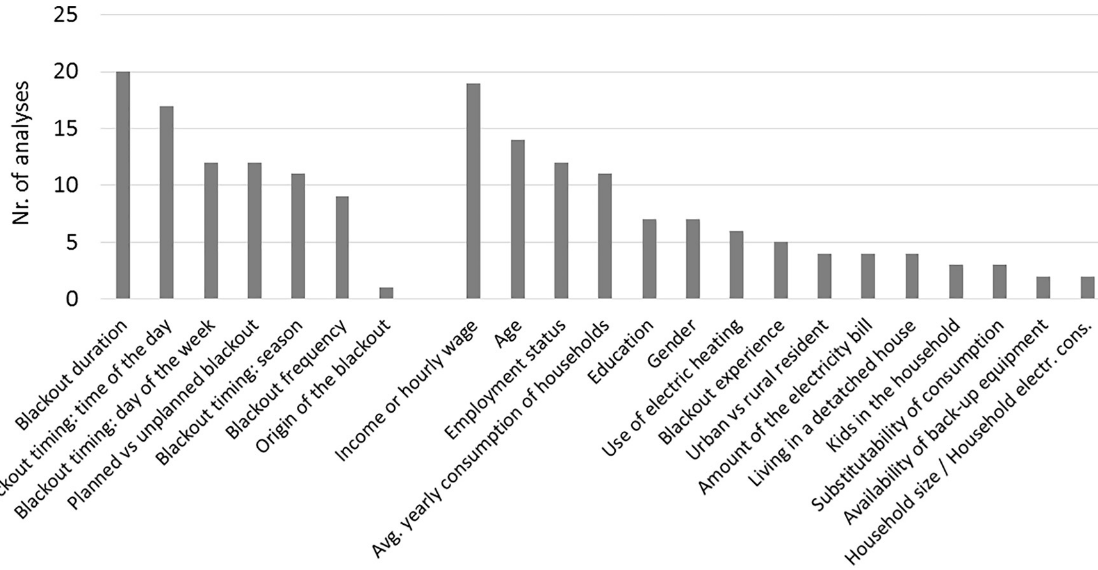

Fig. 1. Drivers of the value of SOES in 41 studies considering residential consumers. Source: author's review.

WTP or WTA values in contingent valuation studies (Carlsson and Martinsson, 2007; Longo et al., 2018; Nkosi and Dikgang, 2018; Niroomand and Jenkins, 2020) or DC experiments (Carlsson and Martinsson, 2008; Bliem, 2009; Abdullah and Mariel, 2010; Pepermans, 2011; Morrissey et al., 2018; Siyaranamual et al., 2020) detect a significant heterogeneity across consumers. Morrissey et al., 2018 explicitly recognize that household preferences toward the SOES are often only partially explained, and call for a deeper investigation of possible drivers.

In the last few years some researchers have taken up this challenge and tried to dig into the psychological determinants of heterogeneity. Pepermans, 2011, for example, incorporates in his study the respondents' attitudes toward the possibility of regularly paying a higher bill in order to reduce outage probability (so-called “WTP attitude”), as well as toward the possibility of accepting a higher outage probability in exchange for a lower electricity bill (“WTA attitude”). His results suggest that the perceived blackout damage is positively correlated to a positive WTP attitude, and negatively correlated to a positive WTA attitude. Furthermore, he finds that the WTP to reduce outage frequency is higher among households who expect a higher outage frequency in the future. Longo et al., 2018 report instead a positive correlation between self-reported environmental sensitivity and a higher WTP for scenarios with less frequent blackouts. They also find that personal values such as egoism or hedonism tend to be associated to a lower WTP to reduce outage frequency with respect to the status quo. A few studies have explored the possible trade-offs or complementarities between the choice of a renewable-based electricity supply versus the choice of a supply ensuring lower blackout frequency or duration. Amador et al., 2013, for example, develop a DC experiment including the risk of blackouts, the availability of an energy auditing service, and finally the renewable content of the electricity supply. They are thus able to disentangle consumer preferences toward the risk of blackouts on the one hand, and consumer preferences for other features of the electricity supply related to environmental sustainability on the other hand. Merk et al., 2019 develop a similar vignette study including both outage duration and frequency, and the renewable content of the electricity supply. Beyond measuring a sizeable heterogeneity in consumer responses, they point out that consumers are ready to pay for renewable-based generation only as long as the continuity of supply is safeguarded. Siyaranamual et al., 2020 develop a DC experiment in which respondents located in Indonesia evaluate at the same time blackout duration, share of hydroelectricity and coal in the supply mix, and finally the increase in the electrification rate in rural areas. They use a random parameter and a latent class specification to detect and explain heterogeneity in the respondents' WTP, and find that the WTP for reducing outage duration is positive in most latent classes, but generally lower than the WTP for increasing the electrification rate and the share of hydroelectric generation. Finally, Sagebiel and Rommel, 2014 develop a DC experiment in Hyderabad, India, to evaluate households' preferences toward blackout frequency, share of renewables in the generation mix, and type of company providing the service. Interestingly, they find that part of the heterogeneity observed in the WTP to improve continuity is connected to the heuristics of the decision process; more specifically, 32.7% of the respondents systematically chose the cheapest options, and neglected the other attributes.

2.4. Our contribution to the literature

Our contribution to the debate concerning the value of the SOES in the context of the energy transition is twofold.

First, we analyse the preferences of Swiss households toward variations in the frequency and duration of blackouts on the one hand, and the primary energy sources used for generation on the other hand. We are thus able to evaluate the trade-offs that households perceive between the two dimensions of security and sustainability of electricity supply, and identify whether consumers expect different security levels from specific primary energy sources.

Secondly, we develop a DC model with latent classes: this strategy allows us to include in the analysis not only the observable demographic variables, but also the otherwise unobservable attitudinal drivers that may influence the value that households place on security. Latent classes allow us to identify distinct consumer segments showing heterogeneous preference patterns. The use of class membership functions allows us to further investigate the determinants of the class membership probability, and hence to provide a better description of the demographic, behavioural, and attitudinal characteristics of each market segment. Latent classes significantly improve the model fit and, most importantly, the understanding of consumer behaviour, thus responding to the call emerging from the surveyed literature.

3. Method

As already mentioned, our analysis is based on stated preferences, more specifically on a DC experiment with latent classes and class membership functions.

The backbone of DC analysis is the assumption that a decision maker, when facing a set of mutually exclusive and collectively exhaustive alternatives showing different characteristics – the so-called "attributes" – will select the one providing him/her the highest indirect utility. Individual preferences may be influenced by the alternatives' attributes, but also by the consumer's demographic, behavioural, and attitudinal traits.

The basic specification of DC models, the multinomial logit, assumes that consumer preferences are homogeneous across the sample, after accounting for the relevant demographic variables. The latent class specification assumes instead that market segments showing different preferences can be identified endogenously within the model (Bhat, 1997); thus, it allows the researcher to account for systematic, but otherwise unobserved heterogeneity in consumer behaviour (Bhat, 1997; Gopinath, 1995). Instead of estimating a simple class membership probability for each individual, we model latent classes by means of class membership functions embedded in the DC model and connecting the probability of belonging to each of the latent classes to the relevant demographic, behavioural, or attitudinal drivers. Latent classes, particularly when including a model for class membership instead of a simple probability, provide a better behavioural interpretation of the observed heterogeneity as compared to a random parameter specification, whose very flexible structure is instead mainly useful to quantify the observed heterogeneity under given assumptions as regards the distribution of the parameters (Greene and Hensher, 2003; Hurtubia et al., 2014).

The econometric specification of a DC model with latent classes and class membership functions consists of the following equations (Bhat, 1997):

$$U_{ijt}^{s} = V_{ijt}^{s}(Z_j, X_i, ; \beta^s) + \varepsilon_{ijt}, \text{with } \varepsilon_{ijt} \text{ i.i.d.} \sim EV(0, \mu_\varepsilon) \quad (1)$$

$$y_{ijt} = 1 \text{ if } U_{ijt}^{s} = \max_k \{U_{ikt}^{s}\}, y_{ijt} = 0 \text{ otherwise} \quad (2)$$

$$F_i^s = f(X_i; \gamma^s) + \omega_i^s, \omega_i^s \text{ i.i.d.} \sim EV(0,1) \quad (3)$$

Where:

- U_{ijt}^{s} is the utility that respondent *i*, belonging to class $s \epsilon S$, extracts from choosing alternative *j* from choice set C^s in choice task *t*,
- Z_j is a vector of attributes of alternative *j*,
- X_i is a vector of respondent *i*'s demographic variables,
- y_{ijt} is a dummy variable taking variable 1 if respondent *i* chooses alternative *j* in choice task *t*, and value 0 if *i* chooses a different alternative,
- F_i^s is the class membership function, connecting the characteristics of respondent *i* to the probability that *i* belongs to class *s*,
- β^s and γ^s are class-specific parameters to be estimated.

Thanks to the assumptions made on the distribution of the error terms, the choice probability for each alternative and the class membership probability can be written as follows:

$$P_{it}(j|s) = \frac{e^{V^s(Z_i, X_j; \beta^s)}}{\sum_{k \in C^s} e^{V^s(Z_i, X_k; \beta^s)}} \quad (4)$$

$$P_i(s) = \frac{e^{f(Z_i; \gamma^s)}}{\sum_{r \in S} e^{f(Z_i, \gamma^r)}} \quad (5)$$

Where:

- $P_i(j|s)$ is the probability that respondent *i* chooses alternative *j* in choice task *t*, given that he belongs to class *s*,
- $P_i(s)$ is the probability that respondent *i* belongs to class *s*. If the class membership function F_i^s is omitted, $P_i(s)$ is estimated as such.

The model is estimated via simulated maximum likelihood: the log-likelihood function takes the following form:

$$L = \sum_i \log \left\{ \sum_s \left[P_i(s) * \prod_t \prod_{i \in C^s} P_{it}(j|s)^{y_{ijt}} \right] \right\} \quad (6)$$

To the best of our knowledge, the latent class approach has rarely been used in the analysis of the value of SOES to end consumers: two exceptions are Sagebiel and Rommel, 2014 and Siyaranamual et al., 2020. Their analyses are similar to ours, as both use a latent class DC model to evaluate household preferences toward the risk of blackouts and the use of renewable-based electricity or a hydroelectric supply. However, the contexts in which their studies are conducted (Indian megacities for Sagebiel and Rommel, 2014, Indonesia for Siyaranamual et al., 2020) are very different as compared to Switzerland in terms of outage frequency, structure and problems of the electricity sector, and demographic conditions of households. Moreover, although they both describe specific behavioural patterns corresponding to each latent class, their DC models only estimate a class membership probability; hence, they do not investigate the demographic or attitudinal determinants of heterogeneity directly within the DC model. Drawing from the methodological suggestions of Gopinath, 1995, and Hurtubia et al., 2014, we use instead the available psychometric indicators in the class membership functions together with the relevant demographic variables, and thus evaluate the role of attitudinal drivers in determining consumer preferences directly within the DC model.

4. Data

The DC experiment was administered by means of an on-line survey, translated in French and German and distributed through an independent market research company in January and February 2015. The survey was tested on 100 respondents with satisfactory results; the final sample - including the sub-sample used for the test - consisted of 1006 respondents, stratified according to the main demographic variables in order to ensure representativeness of the population living in the French- and German-speaking regions of Switzerland. A detailed description of the sample is available in Appendix A.

The survey included:

- A short introductory text describing the purpose of the analysis,
- 30 psychometric questions, in which the respondents declared on a 7-points Likert scale their agreement or disagreement with statements concerning renewable energy, nuclear, coal- and gas-fired generation, the local impacts of wind generation, electricity imports, blackouts, increases in electricity prices, climate change, and environmental pollution,
- Questions regarding the respondent's habits and behaviour in the fields of energy consumption and environmental sustainability: environmental friendly facilities adopted in the household, average electricity bill, subscription to a green energy plan, energy-related habits in daily life, experience of a long or short blackout at home or in the workplace in the past 12 months,
- Questions regarding the typical demographic variables: gender, age, nationality, education, region of residence, working status, monthly household income, type of dwelling, number and age of the people living in the household,
- The DC experiment: each respondent was asked to complete seven choice tasks, in which he/she had to select one out of five electricity supply contracts for his/her own dwelling. Table 2 provides an example of a choice task. The DC experiment was introduced by a short text describing the electricity generation mix observed in Switzerland, the

Table 2
Example of a choice task.

Please select the electricity supply contract you would be ready to sign for your own flat or house. You can choose only one contract.					
	Nuclear	Mix - of which 60% from renewables	Hydro	Solar	Wind
Price (centCHF/kWh)	18	27.5	21	24	50
Nr of 5 min blackouts	0	1 per year	1 per year	4 per year	1 per year
Nr of 4 h blackouts	4 per year	4 per year	0	0	0
Your choice:					

average price of electricity in centCHF/kWh, and the average frequency and duration of blackouts in 2013.

The DC experiment included five alternatives, each described by four or five attributes. The first attribute, that was used as a label, described the primary energy source used for generation; the available options were nuclear energy, hydroelectric energy, wind, sun, and a "grey mix" from unspecified sources. The remaining attributes were the price of electricity in centCHF/kWh, the number of short (5 min) blackouts per year, the number of long (4 h) blackouts per year, and finally the share of renewable-based generation from unspecified energy sources in the grey mix alternative. The levels of the attributes were defined based on the current and prospective structure of the electricity generation and retailing activities in Switzerland, and drawing from the experiences of other European countries (Table 3).

The attributes concerning the number of short and long blackouts were described in terms of expected frequency of each kind of blackout during the upcoming year. The respondents were thus asked to select a contract with a given reliability level, rather than to engage in a demand response programme. By expressing the expected blackout frequency in terms of number of blackouts in the upcoming year, we tried to rule out the possible bias connected to the season in which the survey was distributed. Indeed, as reported in chapter 2, some stated preference analyses explicitly mention the season among the blackout attributes, and find that in Norther-European or alpine countries Winter blackouts tend to harm more than Summer ones; to the best of our knowledge, however, no study evaluates the possible consequences of administering a survey in Winter rather than in Summer. By bringing the respondent's attention on a yearly scenario both in the introductory text, and in the description of the blackout attributes, we tried to mitigate the possible bias connected to the fact that our survey was administered in Winter.

The choice tasks were defined using the software NGene through an efficient design with blocking, averaging a random parameter and an error component specification. The final design consisted in eight blocks with seven choice tasks each: each respondent was randomly assigned to one out of the eight blocks.

The fact that each respondent had to complete seven choice tasks with five alternatives each might raise some concern related to respondent's fatigue, attribute non-attendance (Hensher and Greene, 2010) or the use of heuristic decision rules deviating from the standard assumption of random utility maximization underlying discrete choice modelling (Hess et al., 2010). Overall, the survey completion time was around 12 min, a reasonable value for respondents participating in a standing panel and receiving a small compensation for filling in the survey. The inspection of the results suggests moreover that the responses were rather balanced across alternatives and attributes (Tables B.1 and B.2 in Appendix B). As our preliminary estimations did not reveal glaring deviations from the expected random utility maximization, we concluded that this assumption was satisfied, and proceeded with the analysis as explained in the next chapter.

5. Results

Using the software PythonBiogeme (Bierlaire, 2016) we estimated a series of DC models with increasing complexity. We started with a multinomial logit specification including the relevant demographic variables, then tested several latent class specifications with class-specific parameters for the sensitivity to the frequency of short and long blackouts and class membership estimated as a simple probability. Finally, we tested several latent class models with class-specific parameters for blackout sensitivity but including appropriate class membership functions instead of class membership probabilities. This allowed us to investigate the demographic and behavioural characteristics of the respondents belonging to each class. Our preferred specification is a latent class model with three latent classes and class membership functions. We decided to retain this specification as the McFadden adjusted R^2, the BIC, and the AIC indicators showed a continuous improvement along with the inclusion of the second and third latent class and the class membership functions, whereas our attempts to estimate a model with four latent classes resulted in the fourth class repeatedly collapsing into the third one. The estimated parameters are mostly stable across the various specifications: the structure of the model is reasonably robust, and provides sensible insights into households' behaviour. The rest of this section comments on our preferred specification; detailed information concerning the estimated models is collected within Table B.3 in Appendix B.

Table 3
DC experiment: alternatives, attributes, and attribute levels.

Attributes	Units of measure	Levels	Average levels in 2013
Primary energy source (attribute used as a label in the DC experiment)	Kind of primary energy source used for generation	Nuclear, hydro, wind, sun, "grey mix"	"grey mix"
Share of renewables from unspecified sources (attribute only available for the "grey mix" alternative)	% of supply	40%; 60%; 80%; 100%	60%
Frequency of 5 min blackouts	Nr. of 5 min blackouts per year	0; 0.25; 1; 4	0.25
Frequency of 4 h blackouts	Nr. of 4 h blackouts per year	0; 0.25; 1; 4	0.25
Price of electricity	Final price of electricity in centCHF/kWh	14.5, 18, 21, 24, 27.5, 50 (14.5 not available for hydro, sun, wind; 18 not available for sun)	21

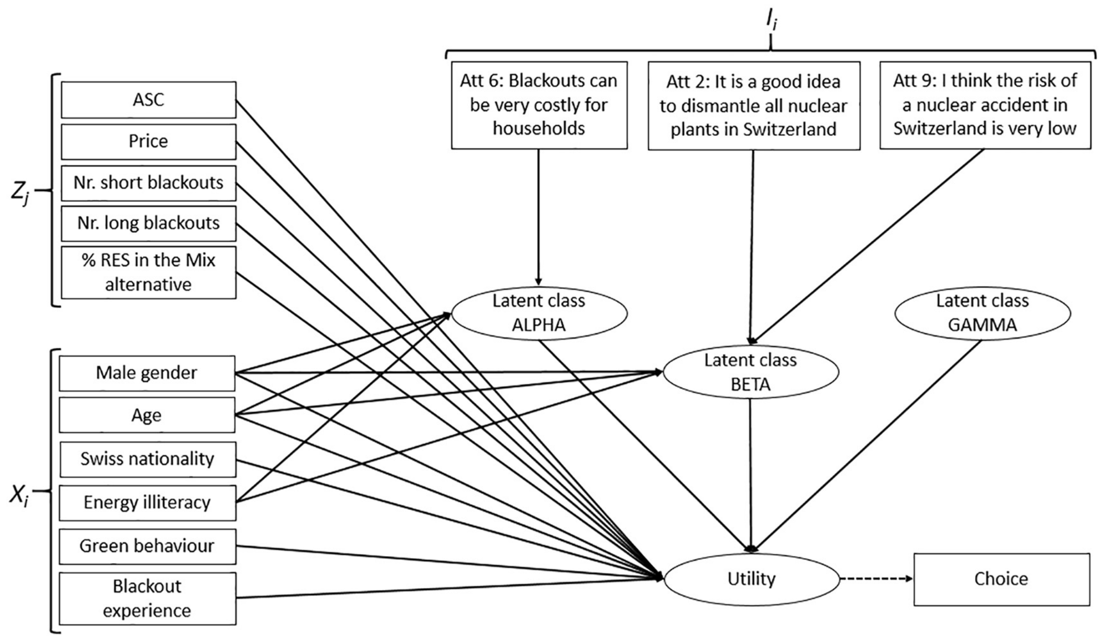

Fig. 2. Scheme of the DC model with three latent classes.

5.1. Estimation results: overview

Fig. 2 provides a visual description of our preferred specification: the image depicts the statistically significant relationships connecting the relevant alternatives' attributes and respondents' characteristics to the respondents' utility, and thereby to the respondents' choices. Following Walker, 2001 we use rectangles for observable variables, ovals for latent constructs, solid arrows for structural equations, and dotted arrows for measurement equations.

Fig. 2 shows that the respondent's utility – and hence his/her choices – depends on the attributes of each alternative electricity supply contract, on a few demographic and behavioural variables characterizing the respondent, and finally on the probability that he/she belongs to one of the three latent classes. The latter is in turn correlated to selected demographic, behavioural, and attitudinal variables, as measured by the class membership functions.

Table 4 collects the detailed results of our estimates: our preferred specification, a latent class model with three latent classes and class membership functions, is compared to a simple multinomial logit to evaluate the robustness of the model structure and the improvements achieved by including latent classes.

5.2. Perceived impact of blackouts

Table 4 suggests that blackout frequency and duration play a substantial role in influencing utility and hence consumer choices: both models show, indeed, that households have a marked sensitivity toward the risk of blackouts. The parameters for an increase in the frequency of short and long blackouts are generally negative and significant: as expected, a higher blackout frequency decreases utility. Long blackouts harm more than short ones: on average, we find that a blackout lasting 4 h harms almost 300% than one lasting 5 min, with sizeable differences across latent classes and energy sources.

Households have, indeed, a different sensitivity to blackout frequency and duration depending on the primary energy source used for generation. The results suggest that they do perceive a connection between the impact of a blackout and the way electricity is generated: the direction in which preferences run depends very much on the attitudinal traits, included in the model through latent classes.

In fact, the latent class model identifies three latent classes, Alpha, Beta, and Gamma, showing very specific preference patterns.

Class Alpha collects approximately 47% of the sample; the probability of belonging to it increases with male gender, older age, a higher score in the energy illiteracy index, and finally a stronger agreement with an attitudinal statement concerning the risk that blackouts can cause high costs to households. The attitudinal indicator included in the definition of class Alpha, as those picked for class Beta, was selected based on a principal component analysis of the available indicators, which identified three main dimensions, namely environmental concern, risk aversion, and optimism as concerns nuclear generation. Looking at the preferences toward security, Alpha respondents show relatively stable coefficients for blackout frequency, with a moderately higher aversion to blackouts associated to sun- and wind-based supplies, and a small, but positive coefficient for short blackouts associated to the grey mix. Long blackouts harm from 1.2 to 3.5 times more than short blackouts; the biggest difference is observed for the grey mix and the nuclear-based supply.

Class Beta collects another 47% of the sample; the probability of belonging to it is positively correlated to male gender, a higher score in the energy illiteracy index, a younger age, and finally a negative attitude toward nuclear generation. Indeed, Beta respondents tend to agree with the nuclear phase-out in Switzerland, and disagree with the idea that the risk of a nuclear accident in the country is low. Their preferences with respect to blackouts and primary energy sources signal a strong dislike for blackouts associated to a nuclear-based supply: the blackout coefficients are in this case 13 to 14 times larger than the averages for the remaining energy sources, depending on blackout length. The aversion to blackouts associated to a sun-, wind-, or hydro-based supply is instead particularly low in the case of short blackouts, and in line with that observed for the grey mix in the case of long blackouts. The damage perceived from longer blackouts is 1.7 times higher than that associated to short blackouts for the grey mix, around 4 times higher for wind-based and nuclear generation, 12 times higher for the hydroelectric option, and 14 times higher for sun-based generation.

Class Gamma collects the remaining 6% of the sample. This class is described as the residual group with respect to classes Alpha and Beta:

Table 4
Results.

	M1 Multinomial logit	M2 Three latent classes with class membership functions		
Nr of observations	1006	1006		
Nr of estimated parameters	31	61		
Model fit				
Final log-likelihood	−8725.2	−8042.7		
McFadden adjusted R2	0.227	0.3		
AIC	17,512.4	16,207.4		
BIC	17,664.7	16,507.2		
Estimated parameters				
Alternative-specific constants				
Hydro	0.572**	0.169		
Nuclear	−0.0683	−0.0531***		
Sun	0.672***	0.589**		
Wind	1.24***	1.25**		
Price				
Hydro	−0.0573***	−0.0568***		
Mix	−0.062***	−0.0715***		
Nuclear	−0.0927***	−0.0873***		
Sun	−0.0481***	−0.0629***		
Wind	−0.0801***	−0.0932***		
Share of renewable electricity in the mix alternative				
40% RES	−0.0249	−0.438***		
80% RES	0.0836	0.145		
100% RES	0.559***	0.646**		
Demographic variables				
Age_mix	0.0147***	0.0129**		
Green_behaviour[a]_nuclear	−0.445***	−0.439***		
Blackout_experience[b]_nuclear	0.289***	0.241**		
Illiteracy[c]_nuclear	−0.0603	−0.0752***		
Swiss_nuclear	−0.00209***	−0.00147***		
Male_hydro	0.249**	0.231**		
Male_nuclear	0.756***	0.797**		
Male_sun	−0.33***	−0.157***		
Male_wind	0.065	0.00524		
Long blackouts		Class Alpha	Class Beta	Class Gamma
Hydro	−0.448***	−0.336***	−0.669***	−0.669***
Mix	−0.285***	−0.138***	−0.745***	−0.534***
Nuclear	−0.284***	−0.188***	−10.3***	−22.2***
Sun	−0.436***	−0.571***	−0.765***	0.444**
Wind	−0.566***	−0.61***	−0.664***	−3.26***
Short blackouts		Class Alpha	Class Beta	Class Gamma
Hydro	−0.128***	−0.198***	−0.0554***	−1.17***
Mix	−0.0665***	0.109**	−0.43***	−0.589***
Nuclear	−0.145***	−0.0541***	−2.28***	−8.52***
Sun	−0.139***	−0.505***	−0.0531***	0.621**
Wind	−0.216***	−0.508***	−0.159***	−0.672***
Parameters of the class membership functions		Class Alpha	Class Beta	Class Gamma
Green_behaviour		0.0659		
Age		0.0179**	−0.0019***	
Illiteracy		0.461**	0.398**	
Male		1.99**	2.22**	
Att6 - Blackouts can be very costly for households		0.0774*		
Att2 - It is a good idea to dismantle all nuclear plants in Switzerland			0.341**	
Att9 - I think the risk of a nuclear accident in Switzerland is very low			−0.123***	
Estimated size of each class^		46.7%	47.1%	6.1%

* *p*-value ≤0.1, ** p-value ≤0.05, *** *p*-value ≤0.01; ^ class size computed from the estimated parameters.

[a] "Green behaviour" is an index ranging from 0 to 3 and counting whether the respondent switches lights off when not needed, lowers the heating at night, and has a renewable-based electricity contract for his/her own dwelling.

[b] "Blackout experience" is a dummy variable equal to 1 if the respondent has experienced at least one blackout at home or in the workplace in the past 12 months, and 0 otherwise.

[c] "Illiteracy": the energy illiteracy index, ranging from 0 to 8, counts how many times a respondent answers "I don't know" to questions concerning his/her own electricity bill and the energy saving or renewable-based facilities installed in his/her dwelling.

thus, its members are more likely to be energy literate, women, younger than the members of class Alpha, and slightly older than those of class Beta. Class Gamma respondents show very radical preferences with respect to blackouts coming from specific primary energy sources. They record, indeed, a deep aversion to interruptions in a nuclear-based supply: the coefficients are negative and more than double in magnitude than the already large ones expressed by Beta respondents. On the other hand, Gamma respondents express small, but positive coefficients for short and long blackouts associated to a sun-based supply. The blackouts associated to the remaining alternatives record negative, but more stable coefficients, several times smaller than those associated to the interruptions in the nuclear-based option. The perceived difference between long and short blackouts is less extreme as compared to class Beta. Indeed, the coefficients for longer blackouts are around the same size as those for short ones in the case of sun-based supplies and the grey mix, slightly more than double for hydro- and nuclear-based contracts, and around 4.8 times larger for the wind-based option.

The fact that two groups of respondents express small, but positive coefficients for an increased blackout frequency if the electricity supply comes from specific supply options deserves more attention. There are, indeed, a few studies exploiting random parameter techniques (Nkosi and Dikgang, 2018; Niroomand and Jenkins, 2020) that find a counter-intuitive, positive impact of blackouts on utility for a small subset of the respondents, although in a very different setting. In our case the positive blackout coefficients, rather than signalling a low interest in the SOES, might suggest that some respondents are so attached to a specific energy source, or to the current structure of the electricity system, that they choose it even if it is, or becomes, less reliable. Class Gamma respondents, for example, might think that solar generation is inherently unpredictable and hence more subject to blackouts, or that its lower emission levels make it more desirable than other generation technologies even if it is less reliable. Alternatively, they might consider that a blackout in a sun-based supply, even if caused by an accident in the generation facilities, is not necessarily dangerous for the local residents, as it could be the case for nuclear generation or other large-scale generation technologies. The fact that class Alpha respondents are instead ready to accept a higher frequency of short blackouts in the grey mix alternative might suggest that they might be willing to bear a slightly lower security level if this means that the electricity system will not undergo the deep transformation implied by the energy transition. In this case, the weaker opposition to blackouts could stem from a preference for the current structure of the electricity system, characterized by a top-down functioning, featuring a passive role for consumers, and largely based on large-scale generation plants that are often less visible in everyday life.

The comparison of the blackout coefficients across the three classes suggest another interesting remark: besides measuring class-specific preferences toward blackouts associated to each primary energy source, the results also reflect a class-specific attitude toward change in the electricity system in general. Class Alpha respondents seem indeed reluctant to accept a sizeable increase in the contribution of the new renewable-based generation technologies unless they ensure a high level of security. Beta respondents welcome a nuclear phase-out, but they are ready to accept a somewhat higher risk of blackouts connected to the use of renewables only if the expected blackouts are short. Finally, Gamma respondents are the strongest advocates of a nuclear phase-out and require a near-zero risk of blackout if they have to accept nuclear generation, but at the same time ready to opt for solar generation even if it is associated to a higher risk of blackout.

Lastly, it is interesting to note that blackouts enter the models in linear form: this means that an increase in the frequency of blackouts has a constant impact on consumer utility, irrespective of the initial blackout frequency. The linear specification was retained after testing several alternative models, including a quadratic specification, one where each frequency level entered as a dummy variable, and one considering increases and declines with respect to the average blackout frequency recorded in Switzerland in 2013, that was mentioned in the short text introducing the DC experiment. Our results suggest, indeed, that even the possibility of experiencing one short blackout every four years elicited a negative response: coherently with the comments collected during the design of the survey, the perceived blackout frequency among Swiss households is very close to zero.

5.3. WTA for blackouts

Together with the impact of blackouts, our model estimates the effect on consumer utility of price increases in the different alternatives. The results suggest that the respondents' preferences with respect to each primary energy source also translate into different sensitivities to price increases depending on the primary source used for generation. Table 4 shows that price increases have, as expected, a negative effect on utility; the strongest negative impact is recorded for the wind- and nuclear-based contracts, the weakest for solar and hydroelectric generation.

The different sensitivity to price increases depending on the primary energy source used has interesting implications for the assessment of the value of security. Indeed, by estimating price and blackout sensitivities within the same DC model, we are able to compute the WTA of households for an additional short or long blackout throughout a year as a ratio between the appropriate blackout and price coefficients. Table 5 collects the WTA values based on the results obtained through our latent class specification; as a term of comparison, the average price of electricity for the household segment in 2013 was around 21 centCHF/kWh.

The WTA estimates suggest that consumers place, on average, a very high value on the SOES. The figures span however on a wide interval, ranging from close to zero or even negative values to more than 10 times the average price of electricity, depending on the blackout length, primary energy source used, and market segment.

The extreme WTA values observed for the nuclear-based supply in latent classes Beta and Gamma suggest that these respondents feel deeply entitled to an uninterrupted electricity supply if their electricity comes from this technology. Beta respondents also express low WTA values for short blackouts associated to renewable-based contracts, ranging between 4% and 8% if current electricity prices; when it comes to long blackouts, however, the WTA values associated to renewable-based supplies and the grey mix are comparable and range between 33% and 55% of current prices. These results suggest that Beta respondents might be ready to trade a few short blackouts for an environmental friendly and cheaper supply, but are far less ready to accept an increase in the frequency of long blackouts irrespective of the primary energy source used. Gamma respondents express instead a very high WTA for blackouts associated to a hydroelectric supply, and a negative WTA for blackouts associated to a solar supply. These reactions suggest that Gamma respondents could be very reluctant or even virtually unavailable to accept any worsening of the SOES if their country or supplier do not engage in the energy transition, and might be ready to engage with demand response schemes or a private backup solution in order to support the growth of solar generation. At the opposite side of the spectrum, the respondents belonging to class Alpha express a relatively low opposition to short and long blackouts from the traditional generation technologies, such as nuclear, the grey mix, and hydroelectricity, and request instead a better performance from the new sources whose contribution is projected to grow in the next few years. Despite adopting a more demanding perspective when considering solar and wind generation, however, class Alpha respondents express reasonable WTA values, always well below 50% of the current electricity

Table 5
Estimated WTA for accepting a blackout of the selected type.

Class Alpha, WTA in cent CHF/kWh		Class Beta, WTA in cent CHF/kWh		Class Gamma, WTA in cent CHF/kWh	
Short blackouts		Short blackouts		Short blackouts	
Hydro	3.49***	Hydro	0.98*	Hydro	20.6**
Mix	−1.52***	Mix	6.01***	Mix	8.24***
Nuclear	0.62	Nuclear	26.12***	Nuclear	97.59***
Sun	8.03***	Sun	0.84*	Sun	−9.87***
Wind	5.45***	Wind	1.71***	Wind	7.21**
Long blackouts		Long blackouts		Long blackouts	
Hydro	5.92***	Hydro	11.78***	Hydro	46.13***
Mix	1.93***	Mix	10.42***	Mix	7.47***
Nuclear	2.15***	Nuclear	117.98***	Nuclear	254.3***
Sun	9.08***	Sun	12.16***	Sun	−7.06***
Wind	6.55***	Wind	7.12***	Wind	34.98***

* p-value ≤0.1, ** p-value ≤0.05, *** *p*-value ≤0.01. Confidence intervals computed via Delta method.

prices and, on average, around 15% of current electricity prices for short blackouts and 25% for long blackouts.

The WTA estimates collected in Table 5 are net of the impact of several possible confounding factors. Indeed, as reported in Table 4, a variation in the share of renewables included in the grey mix with respect to the current average level of 60% impacts consumer choices (coefficients "*40% RES*", "*80% RES*", and "*100% RES*"). Moreover, a few demographic and behavioural variables, i.e. gender, age, Swiss nationality, previous blackout experience, energy illiteracy, and regular engagement in environmental friendly behaviour further contribute to shaping consumer preferences with respect to each primary energy source. These variables were selected based on the suggestions of the economic literature and retained, after testing several interactions, as they proved significant; in a few cases, they were retained despite not being significant as it was interesting to check that they weren't. Although the literature regarding the drivers of households' preferences with respect to selected primary energy sources does not provide univocal evidence as regards the role of demographic variables, the sign of the estimated coefficients is broadly consistent with some comparable studies. While a detailed comment of the drivers of consumer preferences with respect to each primary energy source per se is outside the focus of this analysis, it is useful to remind that by including these variables into our model, we are able to disentangle consumer preferences with respect to blackouts from other factors influencing individual choices among the available options.

Generally speaking, the fact that our estimates for the value of SOES span over such a wide interval might also suggest that the large variability observed in the literature (Table 1) could be determined not only by the different structure of the electricity sector and consumption habits observed in the various countries, but also by the inherent heterogeneity of consumer reactions in the different contexts, as well as by a structural taste variability. The studies exploiting random parameters measure the magnitude of taste heterogeneity, but do not investigate the existence of specific preference patterns; our approach exploiting latent classes with class membership functions provides instead an assessment of the otherwise unobservable trends in consumer behaviour and an evaluation of the demographic and behavioural drivers that may determine them.

6. Conclusions

An assessment of the value of SOES to electricity consumers is increasingly important in the context of the energy transition, where policy makers, energy regulators, and energy companies will need to decide on large-scale investments, structure and functioning of the energy markets, and strategies to involve consumers and elicit citizens' consensus.

Our contribution sheds light on the value of the SOES for residential consumers in Switzerland. By means of a DC model with latent classes applied to stated preference data, we evaluate the WTA of Swiss households for accepting an increase in the frequency of short and long blackouts. Our analysis improves on the existing literature in two directions. First, by accounting for consumer preferences toward alternative primary energy sources used for producing electricity, we are able to explore the connections or trade-offs that consumers may perceive between security and sustainability, or between the risk of (and from) blackouts and the use of specific primary energy sources. Secondly, the use of a DC model with latent classes and class membership functions allows us to investigate the demographic, behavioural, and attitudinal drivers of consumer preferences, and identify three market segments showing different preference patterns.

We find that the WTA of Swiss households for an increased blackout frequency spans over a very wide interval, ranging from slightly negative values up to more than 10 times the actual electricity prices, depending on the characteristics of the blackout, the primary energy sources used for generation, and the individual characteristics of the residential consumers. According to our estimates, the kind of energy source used is the main driver of consumer WTA; different market segments have radically diverging preferences in this respect.

More in detail, we identify three latent classes showing the following preference patterns:

- Class Alpha, corresponding to around 47% of the respondents, collects individuals showing a mild aversion toward blackouts and a comparably lower availability to accept them if they come from the new generation technologies;
- Class Beta, about the same size as class Alpha, collects environmentally concerned consumers who place a high value on security, are in favour of the nuclear decommissioning, and are more ready to accept blackouts if they are short and associated to sun-, hydro-, or wind-based generation;
- Class Gamma, consisting of the remaining 6% of the sample, gathers respondents who express a strong aversion to the risk of blackouts, but with source-specific WTA values stretching over a very wide range of values. Indeed, Gamma respondents show a negative WTA for blackouts associated to a sun-based supply, and a WTA above 10 times the current electricity prices for long blackouts from a nuclear-based supply. Generally speaking, Gamma respondents might be seen as radical supporters of the nuclear phase-out and of an uptake of solar energy in Switzerland.

Overall, the latent class profiles also suggest that preferences for change or stability of the electricity system are another important driver of heterogeneity in the responses of residential consumers to the risk of blackouts.

Several researchers (Longo et al., 2018; Morrissey et al., 2018; Niroomand and Jenkins, 2020; Siyaranamual et al., 2020) have recently measured a significant heterogeneity in households' preferences with respect to the SOES, and highlighted the need of a deeper investigation of the drivers of household behaviour. Merk et al., 2019 have pointed out that German and British households perceive a trade-off between an expansion in the share of renewables and the SOES, and prioritize the security over the sustainability of their electricity supply. Our findings contribute to a better understanding of the drivers of consumer preferences, and shed further light on households' attitudes toward the primary energy sources involved in the energy transition. Besides filling a gap in the literature concerning the value of security and its determinants, our results may support the evaluation of investments in new generation capacity and in the upgrading of the transmission and distribution grids, and serve as a basis for the design of customized electricity supply contracts matching the expectations of different market segments as regards the SOES and the future of the electric system. Furthermore, despite being focussed on the Swiss households and electric system, our results may be of use for any industrialized country facing the challenge of decarbonizing the energy system and reducing at the same time the contribution of existing nuclear generation plants.

There are, of course, some limitations that may constrain the practical use of our results. First, as already mentioned in chapter 2, the external validity of stated preferences analyses is often questioned, particularly when the respondents face a choice that they rarely or never make in real life. Furthermore, some researchers argue that WTA assessments tend to overestimate the real value of security for electricity consumers. Finally, the fact that our DC experiment did not include an attribute for the advance notice somehow limits the possibility of exploiting these results as an input to design demand response schemes targeting specific household segments. As the contributions from the new generation technologies increase and new technological solutions allow for the introduction of smart contractual arrangements, a new experiment to investigate household choices among real, customized supply contracts could validate our results and further expand our understanding of household preferences and their drivers.

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Appendix A. Description of the sample

Table A.1
Descriptive statistics for the sample and the Swiss population.[a]

Gender	Sample	Population (2015)
Men	49.1%	49.5%
Women	50.9%	50.5%
Age group		
15–29	27.9%	27.3%
30–44	31.1%	32.0%
45–59	33.0%	33.9%
60–64	8.0%	6.8%
Language		
German	73.9%	74.0%
French	26.1%	26.0%
Lives in:		
Cities and agglomerations	79.1%	73.8%
Countryside	20.9%	26.2%
Nationality		
Swiss	80.4%	75.7%

[a] The descriptive statistics for the Swiss population are based on the census published by the Swiss Federal Office of Statistics.

Table A.2
Sample description: consumption pattern, green behaviour, and previous blackout experience.

Green equipment	Yes	I don't know
Insulating window panes	82%	4%
Insulating walls	62%	15%
Solar heating	11%	5%
Photovoltaic panels	7%	3%
Minergie standard	13%	13%
Other energy saving equipment	21%	26%
Other renewable energy equipment	8%	19%
Green behaviour		
Light off when not needed	91%	
Heating off at night	65%	
Renewable electricity contract	44%	38%
In charge of paying electricity bill	81%	
Electricity bill per semester		
Below 200 CHF	25%	
201–400 CHF	38%	
401–800 CHF	13%	
Above 800 CHF	3%	
I don't know		21%
Blackout experience		
Short blackout at home	27%	
Short blackout at work	10%	
Long blackout at home	21%	
Long blackout at work	8%	

Table A.3
Sample description: evaluation of statements concerning environmental or energy issues.

Please evaluate each of these statements by stating how much you agree with it on a scale from 1 to 7. 1 means "Completely disagree", 7 means "Completely agree"	Average	Std. Dev.
Building new generation plants is essential to satisfy the increasing demand for electricity	4.74	1.70
Building new electricity generation plants from renewable energy sources is essential to satisfy the increasing demand for electricity	5.95	1.32
It is important to generate electricity using renewable energy sources	6.36	1.04
Most private buildings should be endowed with solar or photovoltaic panels	5.59	1.53

Table A.3 (*continued*)

Please evaluate each of these statements by stating how much you agree with it on a scale from 1 to 7. 1 means "Completely disagree", 7 means "Completely agree"	Average	Std. Dev.
Wind turbines are noisy, which bothers the people who live near them	3.10	1.60
Wind turbines are dangerous for migrant birds and damage the fauna	3.32	1.55
Wind turbines spoil the scenery	2.86	1.69
I'm not worried about the risk of a nuclear accident in Switzerland	3.36	1.98
I think the risk of a nuclear accident in Switzerland is very low	4.22	1.84
It is a good idea to dismantle all nuclear plants in Switzerland	5.14	1.96
It is dangerous to live close to a nuclear generation plant	4.60	1.92
It is dangerous to live close to a coal-fired generation plant	4.27	1.65
It is dangerous to live close to a gas-fired generation plant	3.88	1.60
Electricity can be imported from foreign countries with no risk	3.16	1.58
It is safe to import electricity from abroad	3.40	1.49
I feel worried about depending on foreign countries for energy supplies	4.40	1.64
Depending on foreign countries for our energy supplies endangers our economy	4.51	1.57
Carbon dioxide from burning coal, oil, and natural gas is causing global warming	5.83	1.31
I find blackouts annoying	4.94	1.67
Blackouts can be very costly for private companies	5.28	1.47
Blackouts can be very costly for households	4.05	1.73
I feel in danger when a blackout occurs at my place	2.45	1.50
I am worried about the risk of future increases in electricity prices	4.36	1.75
If global warming does occur, it would be bad for people and the environment	5.98	1.29
I am worried about the consequences of pollution	5.84	1.30
I am worried about the consequences of climate change	5.52	1.50
Everyone should behave in an environmental friendly way	6.36	1.03
As a society, we should be using less oil, coal, and natural gas in order to reduce environmental impacts on land, water, and air quality	5.92	1.28
It is important to save energy in everyday consumption	6.21	1.12
It is my responsibility to behave in an environmental friendly way	5.96	1.25

Appendix B. Choice experiments: results

Table B.1
Outcomes of the choice experiment: alternatives chosen by primary energy source.

	Nuclear	Mix	Wind	Hydro	Sun
Nr. of times this alternative was chosen	390 (5.5%)	2166 (30.8%)	1466 (20.8%)	1519 (21.6%)	1501 (21.3%)
Nr. of respondents who always chose this alternative	3 (0.3%)	42 (4.2%)	5 (0.5%)	6 (0.6%)	29 (2.9%)
Nr. of respondents who never chose this alternative	806 (80.1%)	222 (22.1%)	309 (30.7%)	304 (30.2%)	355 (35.2%)

Nr. of respondents: 1006; nr. of choice tasks completed: 7042.

Table B.2
Outcomes of the choice experiment: alternatives chosen by price and frequency of long and short blackouts.

	Alternative with the lowest price	Alternative with the lowest nr. of short blackouts	Alternative with the lowest nr. of long blackouts	Alternative with the lowest total nr. of blackouts
Nr. of times this alternative was chosen	2015 (28.6%)	1333 (18.9%)	1772 (25.2%)	2115 (31.4%)
Nr. of respondents who always chose this alternative	6 (0.6%)	0 (0.0%)	0 (0.0%)	2 (0.2%)

Nr. of respondents: 1006; nr. of choice tasks completed: 7042.

Table B.3
Estimation results: details.

	Multinomial logit	Two latent classes	Two latent classes with class membership functions	Three latent classes	Three latent classes with class membership functions
Nr of observations	1006	1006	1006	1006	1006
Nr of estimated parameters	31	42	46	53	61
Final log-likelihood	−8725.2	−8326.6	−8279.1	−8085.8	−8042.7
McFadden adjusted R2	0.227	0.262	0.265	0.282	0.285
AIC	17,512.4	16,737.2	16,650.3	16,277.7	16,207.4
BIC	17,664.7	16,943.6	16,876.3	16,538.1	16,507.2
Parameters of the utility functions					
Alternative-specific constants (ASC)					
ASC_hydro	0.572**	0.0474	0.142	0.108	0.169
ASC_nuclear	−0.0683	−0.576	−0.0475	−0.619	−0.0531***
ASC_sun	0.672***	0.445	0.548**	0.479*	0.589**

(continued on next page)

Table B.3 (*continued*)

	Multinomial logit	Two latent classes	Two latent classes with class membership functions	Three latent classes	Three latent classes with class membership functions
Nr of observations	1006	1006	1006	1006	1006
Nr of estimated parameters	31	42	46	53	61
ASC_wind	1.24***	0.976***	1.02***	1.16***	1.25**
Price					
Price_hydro	−0.0573***	−0.0564***	−0.0561***	−0.0577***	−0.0568***
Price_mix	−0.062***	−0.0727***	−0.0715***	−0.0726***	−0.0715***
Price_nuclear	−0.0927***	−0.0827***	−0.0861***	−0.084***	−0.0873***
Price_sun	−0.0481***	−0.0542***	−0.0546***	−0.0621***	−0.0629***
Price_wind	−0.0801***	−0.0858***	−0.0848***	−0.0927***	−0.0932***
Share of renewable electricity in the mix alternative					
Mix_40%_RES	−0.0249	−0.449	−0.374	−0.597**	−0.438***
Mix_80%_RES	0.0836	0.133	0.122	0.102	0.145
Mix_100%_RES	0.559***	0.682***	0.671***	0.621***	0.646**
Demographic variables					
Age_mix	0.0147***	0.0126***	0.0132***	0.0131***	0.0129**
Green_behaviour_nuclear	−0.445***	−0.477***	−0.441***	−0.469***	−0.439***
Blackout_experience_nuclear	0.289***	0.271***	0.224***	0.281***	0.241**
Illiteracy_nuclear	−0.0603	−0.0674	−0.0779	−0.0676	−0.0752***
Swiss_nuclear	−0.00209***	−0.0023***	−0.00147***	−0.0024***	−0.00147***
Male_hydro	0.249**	0.254**	0.269**	0.219*	0.231**
Male_nuclear	0.756***	0.802***	0.799***	0.785***	0.797**
Male_sun	−0.33***	−0.38***	−0.357***	−0.165	−0.157***
Male_wind	0.065	0.0349	0.06	−0.000818	0.00524
Long blackouts					
Long_blackout_hydro	−0.448***				
Alpha_Long_blackout_hydro		−0.292***	−0.343***	−0.313***	−0.336***
Beta_Long_blackout_hydro		−0.623***	−0.602***	−0.632***	−0.669***
Gamma_Long_blackout_hydro				−19.9***	−2.62***
Long_blackout_mix	−0.285***				
Alpha_Long_blackout_mix		−0.123***	−0.149***	−0.106***	−0.138***
Beta_Long_blackout_mix		−0.722***	−0.646***	−0.746***	−0.745***
Gamma_Long_blackout_mix				−0.513**	−0.534***
Long_blackout_nuclear	−0.284***				
Alpha_Long_blackout_nuclear		−0.0714	−0.195***	−0.0279	−0.188***
Beta_Long_blackout_nuclear		−1.43***	−9.42***	−1.21***	−10.3***
Gamma_Long_blackout_nuclear				−17.6***	−22.2***
Long_blackout_sun	−0.436***				
Alpha_Long_blackout_sun		−0.626***	−0.685***	−0.513***	−0.571***
Beta_Long_blackout_sun		−0.493***	−0.478***	−0.753***	−0.765***
Gamma_Long_blackout_sun				0.516**	0.444**
Long_blackout_wind	−0.566***				
Alpha_Long_blackout_wind		−0.549***	−0.592***	−0.553***	−0.61***
Beta_Long_blackout_wind		−0.647***	−0.638***	−0.659***	−0.664***
Gamma_Long_blackout_wind				−3.32***	−3.26***
Short blackouts					
Short_blackout_hydro	−0.128***				
Alpha_Short_blackout_hydro		−0.203*	−0.197***	−0.257***	−0.198***
Beta_Short_blackout_hydro		−0.066	−0.0662**	−0.0452	−0.0554***
Gamma_Short_blackout_hydro				−1.74	−1.17***
Short_blackout_mix	−0.0665***				
Alpha_Short_blackout_mix		0.109*	0.105***	0.143***	0.109**
Beta_Short_blackout_mix		−0.38***	−0.387***	−0.391***	−0.43***
Gamma_Short_blackout_mix				−0.584***	−0.589***
Short_blackout_nuclear	−0.145***				
Alpha_Short_blackout_nuclear		−0.0344	−0.057	−0.0202	−0.0541***
Beta_Short_blackout_nuclear		−0.409***	−2.12***	−0.381***	−2.28***
Gamma_Short_blackout_nucl.				−7.65***	−8.52***
Short_blackout_Sun	−0.139***				
Alpha_Short_blackout_Sun		−0.575***	−0.574***	−0.538***	−0.505***
Beta_Short_blackout_Sun		−0.0179	−0.0104	−0.0723***	−0.0531***
Gamma_Short_blackout_Sun				0.638***	0.621**
Short_blackout_wind	−0.216***				
Alpha_Short_blackout_wind		−0.651***	−0.495***	−0.66***	−0.508***
Beta_Short_blackout_wind		−0.128***	−0.128***	−0.17***	−0.159***
Gamma_Short_blackout_wind				−1.71	−0.672***
Parameters of the class membership functions					
Alpha_Blackout_experience			0.173*		
Alpha_Green_behaviour					0.0659
Alpha_Age					0.0179**
Alpha_Illiteracy					0.461**
Alpha_Male					1.99**
Alpha_att2 - It is a good idea to dismantle all nuclear plants in Switzerland			−0.373***		

Table B.3 (*continued*)

	Multinomial logit	Two latent classes	Two latent classes with class membership functions	Three latent classes	Three latent classes with class membership functions
Nr of observations	1006	1006	1006	1006	1006
Nr of estimated parameters	31	42	46	53	61
Alpha_att22 - I feel worried about depending on foreign countries for energy supplies			0.095**		
Alpha_att28 - It is important to generate electricity using renewable energy sources (wind, water, sun)			0.108*		
Alpha_att6 - Blackouts can be very costly for households			0.127***		0.0774*
Beta_Age					−0.00191***
Beta_Illiteracy					0.398**
Beta_male					2.22**
Beta_att2 - It is a good idea to dismantle all nuclear plants in Switzerland					0.341**
Beta_att9 - I think the risk of a nuclear accident in Switzerland is very low					−0.123***
Class membership probability or estimated size of each class					
P_Alpha/Size class Alpha		0.436***	0.461^	0.389***	0.467^
P_Beta/Size Class Beta		0.564^	0.539^	0.565***	0.471^
P_Gamma/Size class Gamma				0.046^	0.061^

* p-value ≤0.1, ** p-value ≤0.05, *** p-value ≤0.01; ^ class size or class membership probability computed from the estimated parameters.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2021.105179.

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